THERMALLY INSULATED TEST ROAD: STATE ROAD 26 – PERFORMANCE AND TEMPERATURE PREDICTION STUDIES

MARCH 1972 – NUMBER 2

BY

M. M. BOWERS

JHRP

JOINT HIGHWAY RESEARCH PROJECT

PURDUE UNIVERSITY AND

INDIANA STATE HIGHWAY COMMISSION

Progress Report

THERMALLY INSULATED TEST ROAD: STATE ROAD 26
PERFORMANCE AND TEMPERATURE PREDICTION STUDIES

TO: J. F. McLaughlin, Director
Joint Highway Research Project

March 21, 1972

File: 6-10-7

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

Project: C-36-16G

The attached Progress Report by M. M. Bowers, Graduate Assistant in Research on our staff, is on the approved JHRP research project titled "Thermally Insulated Test Road: State Road 26". This report is of the "Performance and Temperature Prediction Studies" of the 1969-1970 season.

The studies on this project are continuing with data collection in progress for the 1971-72 season. A Final Report on the study is planned upon completion of the analyses of these data. As noted in the recommendations for further study of this report some continued data collection in future years may be desirable.

The report is presented to the Board for information and for acceptance as partial fulfillment of the objectives of the research.

Respectfully submitted,

Harold L. Michael
Associate Director

HLM:ms

cc:
W. L. Dolch
R. L. Eskew
W. H. Goetz
W. L. Grecco
M. J. Gutzwiller
G. K. Hallock
M. E. Harr
R. H. Harrell
M. L. Hayes
R. D. Miles
J. W. Miller
C. F. Scholer
M. B. Scott
J. A. Spooner
N. W. Steinkamp
H. R. J. Walsh
K. B. Woods
E. J. Yoder

Progress Report II

THERMALLY INSULATED TEST ROAD: STATE ROAD 26 PERFORMANCE AND TEMPERATURE PREDICTION STUDIES

by

Maurice M. Bowers
Graduate Assistant in Research

Joint Highway Research Project

Project: C-36-16G

File: 6-10-7

Conducted By

Joint Highway Research Project
Engineering Experiment Station
Purdue University

In Cooperation with

Indiana State Highway Commission

Purdue University
Lafayette, Indiana
March 21, 1972

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The writer also wishes to thank Mr. H. R. J. Walsh, Director of the Research and Training Center, Indiana State Highway Commission, West Lafayette, Indiana for his supervision of all phases of the project carried out by the Training Center. The employees of the Training Center who work, or have worked, on the project are too numerous to mention individually, but this in no way diminishes their contribution to the success of the project. The amount of reliable data obtained is a tribute to their care and effort in instrumenting the test sections and in taking and compiling the data.

Messrs. J. Horton, A. Mohan and M. Roy, Graduate Assistants at Purdue University, deserve thanks for their assistance in obtaining computer solutions for the temperature prediction programs, and for their assistance in plotting and analyzing data.

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ABSTRACT

The analysis of the data obtained for the 1969-70 season is discussed and characterized by typical graphical representations. Comparisons of measured temperatures and temperatures predicted using the 2-D heat flow model are presented. In addition, the sensitivity of the 2-D heat flow model is discussed with regards to the required accuracy of the input information.

The design, construction, installation of instruments, data collection, and the development of the 2-D heat flow program have been thoroughly discussed by Stulgis [4][1] Toenniessen [5], and Ho [1]; and therefore are not covered in detail in this report.

Recommendations for further study are presented at the end of the report.

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1. Numbers in brackets refer to listings in the Bibliography, page 102.

INTRODUCTION

In September, 1969 the JHRP Board approved a plan to locate, design and construct a thermally insulated test road in Indiana. In July, 1968 Stulgis [4] reported such a plan. Construction and instrumentation were completed during the 1969 construction season; and, with the exception of a major change in the positions of the temperature sensors, the design followed that proposed by Stulgis. The change in the temperature sensor pattern from that proposed by Stulgis has been discussed by Toenniessen [5] in a progress report submitted in May, 1970. Toenniessen's report also includes discussions on the following items: a) instrumentation, including type of instruments used, preparation and calibration of the temperature sensors (thermistors) prior to installation, and installation procedures; b) construction procedures that were followed in placing and covering the insulation[1]; c) collection and compilation of the data; and d) the two-dimensional heat flow model for predicting ground temperatures.[2] Information presented by Stulgis [4] and Toenniessen [5] is reproduced in this report only as deemed desirable to aid the reader.

The report is divided into two major parts. The first part is concerned with the presentation and analysis of the data, and the second part covers the temperature prediction phase of the investigation.

---

1. The insulating material on this project is STYROFOAM HI brand Plastic Foam, manufactured by the Dow Chemical Company of Midland, Michigan.

2. See Ho [1] for a more complete discussion of the two-dimensional heat flow model.

LOCATION AND DESIGN

The test site is on State Road 26, approximately 13 miles east of Lafayette, and is located just west of the Rossville town limits.

A plan view of the test sections is shown in Figure 1. Figure 2 is a profile of the test sections. Section C is the normal (or control) section. Section A is the same as C except for the presence of the 1-inch thick, 34-feet wide layer of insulation placed at the subgrade surface. In Section B the subbase was eliminated and a 1.5-inch thick, 46-feet wide layer of insulation was placed directly beneath the base course. The thermistors are located at the center of each 200-feet long section, and are installed in the north half of the road only. Figures 3, 4, and 5 show the thermistor positions in Sections A, B, and C, respectively.

PART I - PRESENTATION AND ANALYSIS OF THE DATA

DATA OBTAINED AT THE SITE

Personnel from the Research and Training Center obtained data at the site from November 1969 to November 1970, with emphasis placed on the freezing season. The data included air temperature, ground temperatures, rainfall, and ground water elevation. Soil borings were taken at the site on July 2, 1969. The borings were made on the north half of the highway at stations where the thermistors are located. In addition to the borings, soil samples were obtained from the sides of the 4-feet deep thermistor installation trench at the time the thermistors were installed. Both the trench samples and the

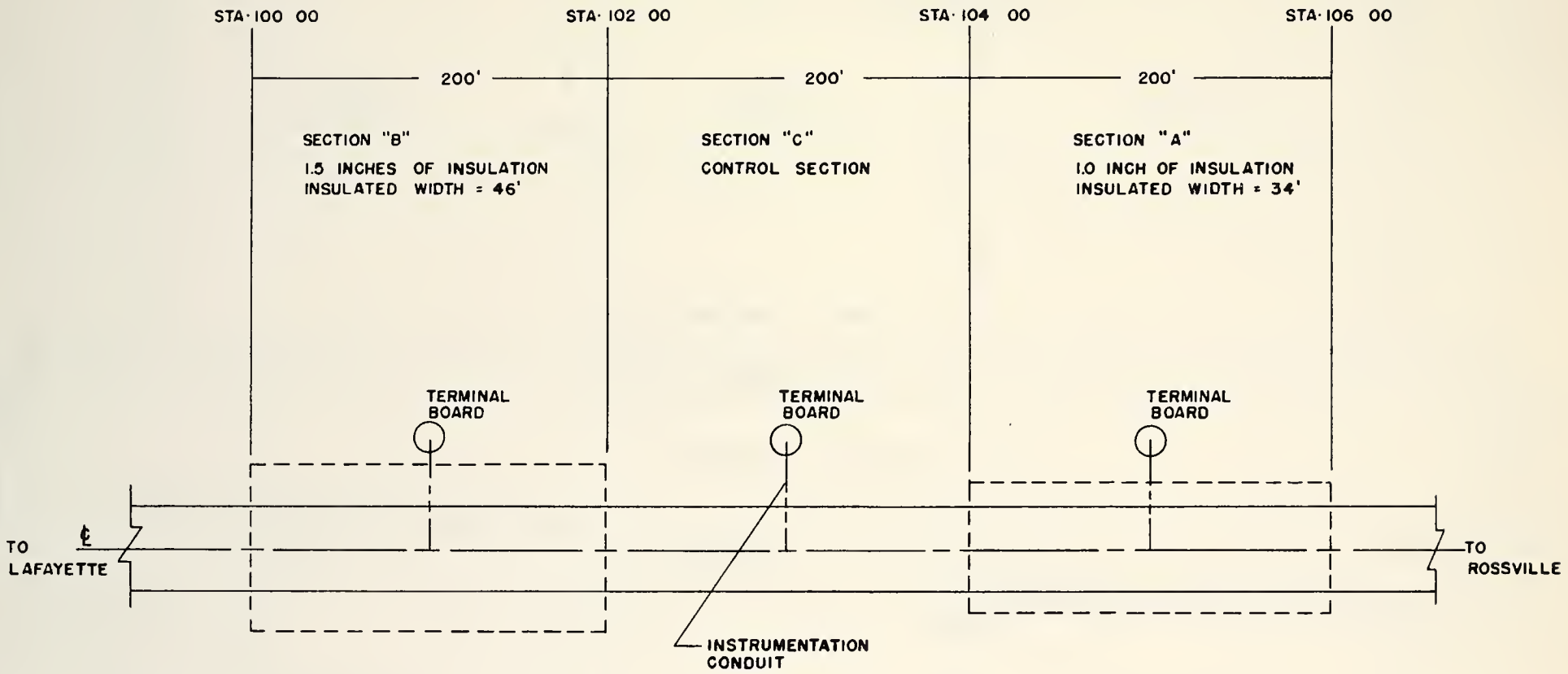
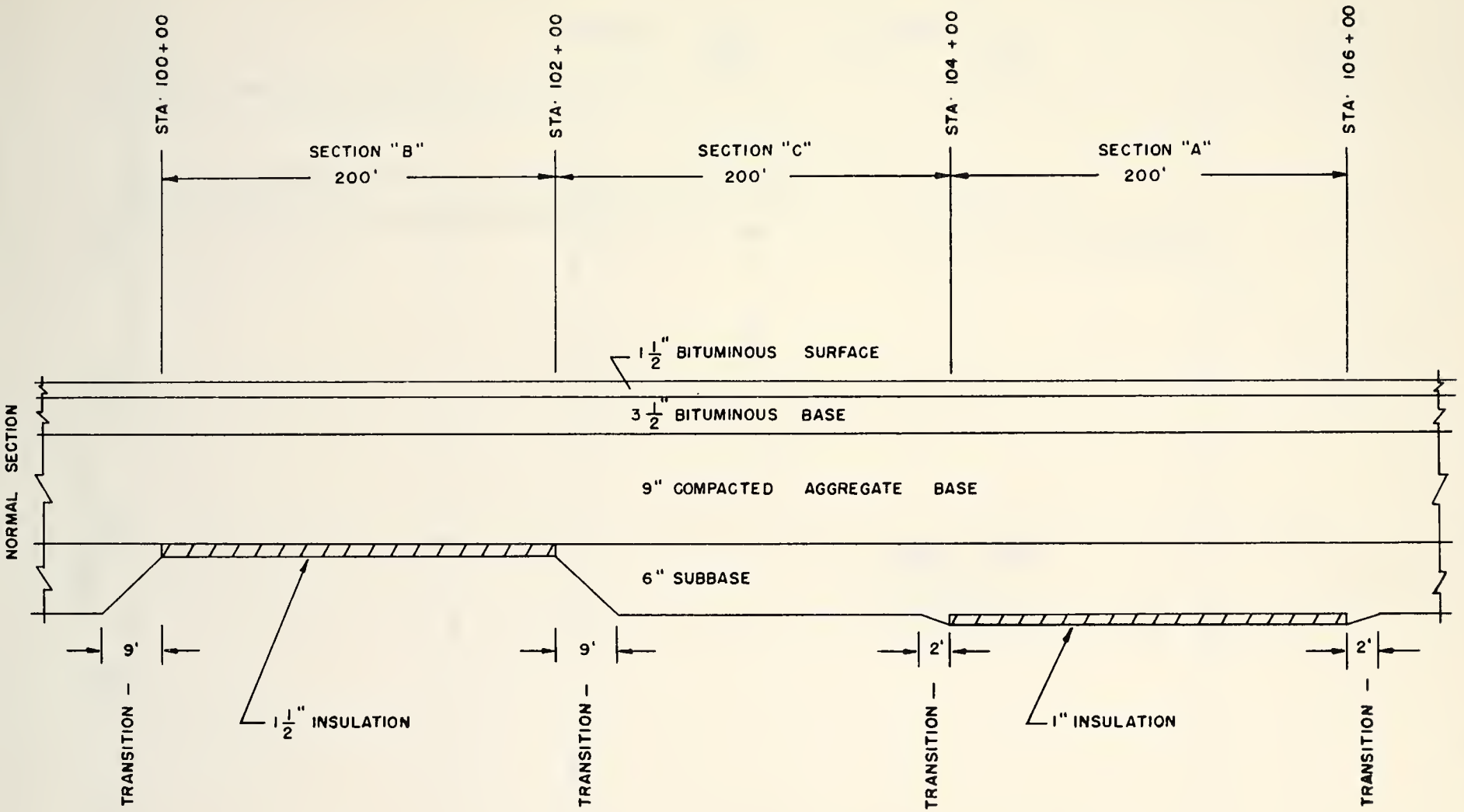


FIGURE 1. PLAN OF FIELD TEST INSTALLATION
STATE ROAD 26 (from Stulgis)

NOT TO SCALE



NOTE: ALL TRANSITIONS AT $\frac{1}{2}$" PER FT.

FIGURE 2 TEST SECTION PROFILE
(from Stulgis)

NOT TO SCALE

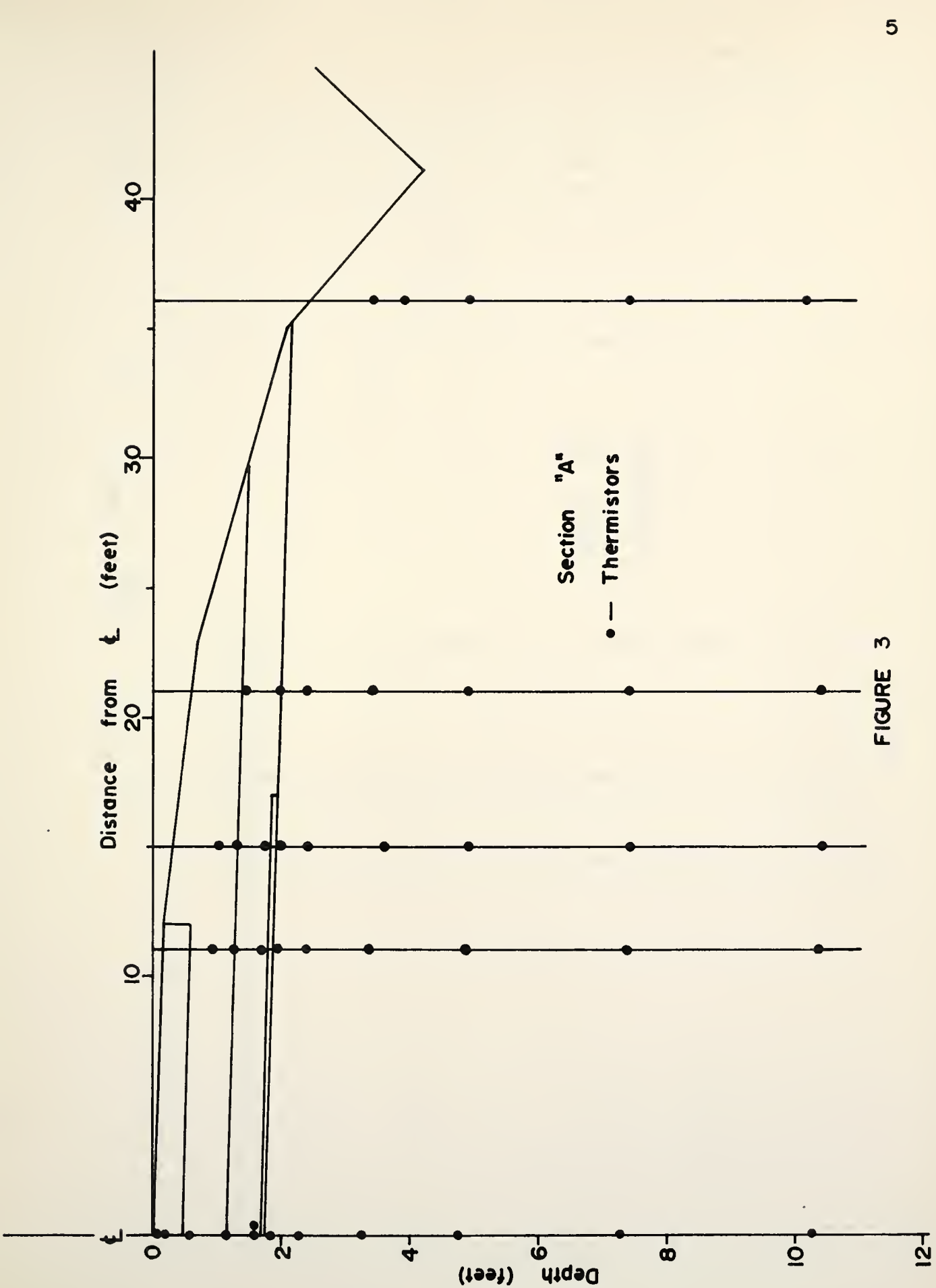

Distance from ℄ (feet)
0
10
20
30
40
Section "A"
• — Thermistors
Depth (feet)
0
2
4
6
8
10
12

FIGURE 3

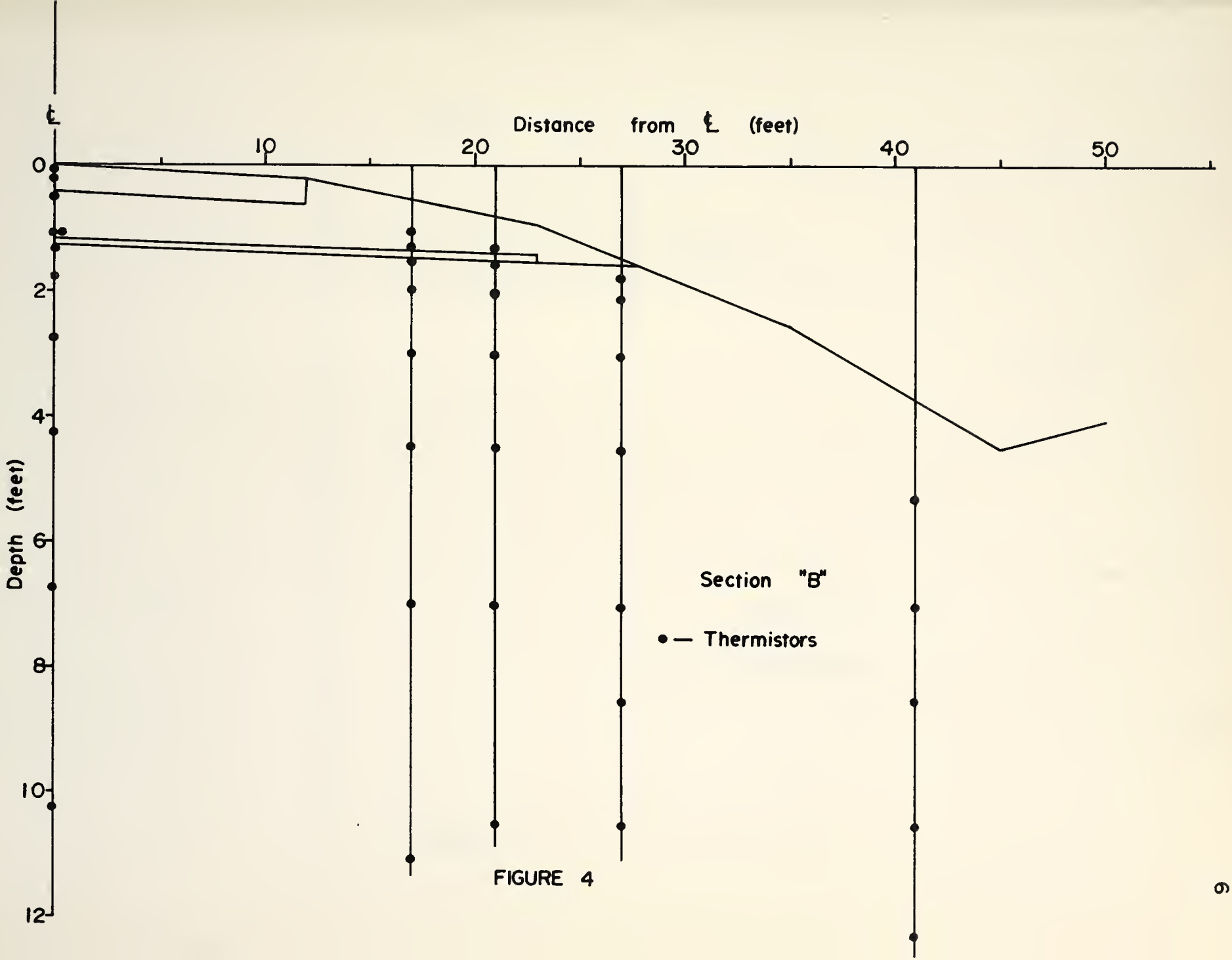

℄
Distance from ℄ (feet)
10
20
30
40
50
0
2
4
6
8
10
12
Depth (feet)
Section "B"
• — Thermistors

FIGURE 4

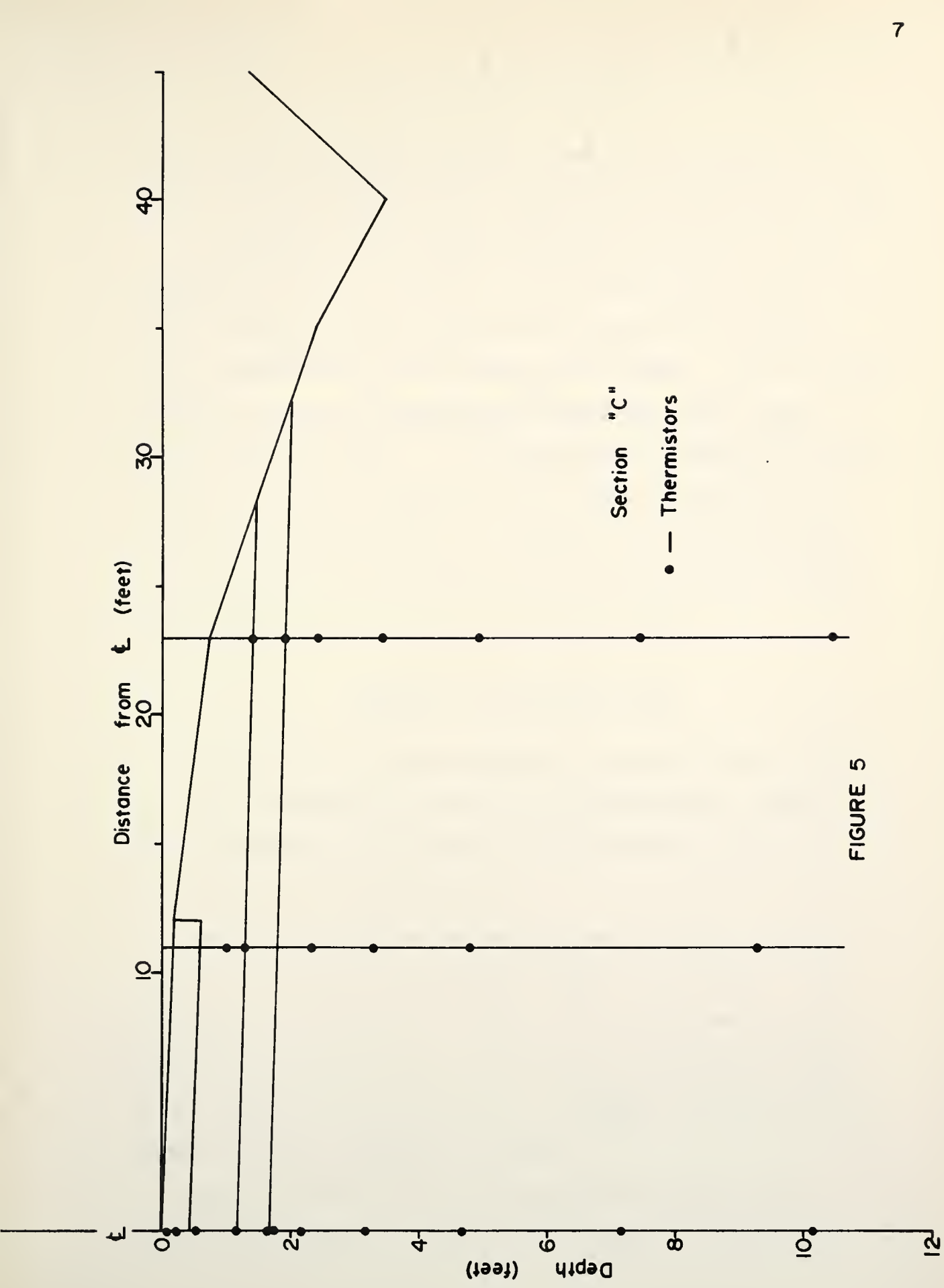

Distance from ℄ (feet)
0
10
20
30
40
℄
Depth (feet)
0
2
4
6
8
10
12
Section "C"
• — Thermistors

FIGURE 5

samples obtained from the borings were analyzed to determine the soil profile at the site and the AASHO classification of the existing soils.

Air temperature was recorded continuously by means of a 7-day thermograph which was located in a standard shelter near the site. Ground temperatures were obtained once per day, with the exception that no readings were taken on weekends and holidays. A non-recording rain gage placed near the thermograph shelter was used to obtain rainfall data at the site. A 1 1/4-inch diameter perforated pipe was installed in the ditch at station 104 to permit observations of the ground water elevation; however, the pipe was not placed deep enough to obtain ground water elevations during the 1969-70 freezing season. The first water appeared in the pipe in May of 1970.

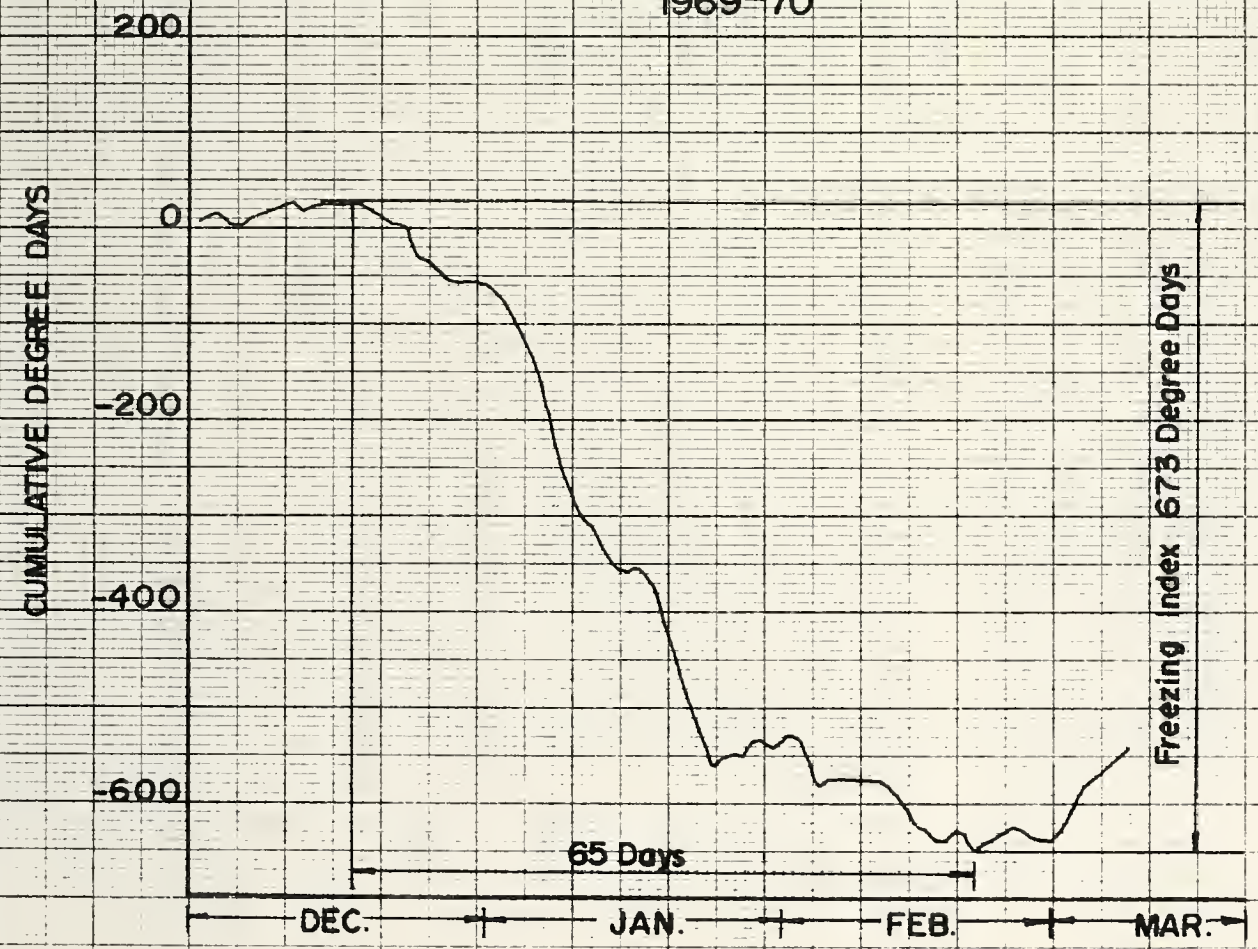
SEVERITY OF THE FREEZING SEASON

For a given set of frost susceptible soil, depth to water table, and exposure conditions, the severity of a given freezing season is generally determined by two factors: a) the freezing index, and b) the duration of the freezing index.

Figure 6 illustrates one method of obtaining both the freezing index and the duration of the freezing index. The reference temperature for such a plot is normally 32°F, and the mean daily air temperature for a given day is generally used to determine the number of degree days for a particular day. Thus degree days per day equals the mean daily air temperature minus 32°F.

Figure 6 is a plot of the data obtained at the site for the 1969-70 freezing season. As shown on the figure, the freezing index

FIGURE 6
DEGREE-DAY CURVE
1969-70



and the duration of the freezing index were 673 degree days and 65 days, respectively. The values are substantially less than the 1274 degree days and 89 days used for the design of the sections, Stulgis [4].

When considering the effect of frost action on the structural performance of a pavement section, it is important to note that a "severe" freezing season is not necessarily one that results in deep frost penetration. The critical period with regards to structural performance is the thawing, i.e., "spring breakup", period, and it has been observed that "spring breakup" is sometimes worse after a moderately cold freezing season than it is after a severely cold freezing season [3].

The important factors governing the amount of damage that occurs during the spring breakup period are the ice content of the soil, the elevation at which the majority of the ice is concentrated, the rate of thawing and the magnitude and number of applied loads. Assuming loads, load repetitions, and thawing rate are all "normal", the critical factors then become those of ice content and the elevation at which the majority of the ice is concentrated. Increases in the ice content of the soil and/or concentration of the ice at higher elevations in the highway section will increase the potential for damage during the thaw period.

For a given set of site conditions the ice content of the soil will increase with decreasing frost penetration rates, because there is more time available for moisture to move to the freezing front. If a moderately cold freezing season results in slower frost penetration rates, then the ice content of the soil will be increased

and the ice will be concentrated at higher elevations in the highway sections. As a result the potential for damage during the thaw period will be greater than for a severely cold season in which the frost penetration rates are significantly higher. Unfortunately the relative coldness of a freezing season is generally determined by the magnitude and duration of the freezing index, and these two parameters do not provide a sufficient basis for evaluating the potential for damage during the thaw period. The magnitude and duration of the freezing index simply fix the end points on the cumulative degree-day curve. Since an infinite number of curves may exist between the two end points, it is the shape of the curve that is important in assessing the potential for "spring breakup". For a given set of site conditions the shape of the cumulative degree-day curve will determine the ice content at a given elevation in the highway section. As a result the damage during the thaw period may be significantly different for two freezing seasons, even though the magnitude and duration of the freezing index are identical for the two seasons.

SOIL AND MOISTURE CONDITIONS AT THE SITE

Soil and moisture conditions at the site are such that one would not normally expect any severe frost heaving to occur, except in Section B. The soils in Section A, from the subgrade surface down, consist of 4 feet of A-2-4 soil (AASHO classification) overlying more than 8 feet of A-1-b soil. The water contents of these soils at the time the soil samples were taken was a low 5 to 6%. Section A was the only section in which the water table was encountered, approximately

14 feet below the pavement surface. Section C soils consist primarily of 1.5 feet of A-2-4 soil overlying A-1-b soil. At a depth of 2 feet there is a layer of A-1-a soil that has an average thickness of 6 inches. The soils in this section also have low water contents of 5 to 7%. The borings in this section extended to a depth of 11.5 feet below the pavement surface, with no water table being encountered. Section B soils consist of 1 foot of A-2-4 soil overlying 3.5 feet of A-4 soil, which in turn overlies an A-6 soil. The water contents of the A-2-4, A-4, and A-6 soils were 5%, 13%, and 17% respectively. One boring in this section extended to a depth of 15 feet without encountering the water table.

Considering the types of soil, water contents, and depth to water table, Sections A and C should be relatively free from any detrimental frost action. Section B, however, could exhibit considerable heaving during the more moderate freezing seasons; but it will not do so now because of the presence of the insulation.

The fact that the real site conditions differ considerably from those expected (and desired) does not significantly affect the evaluation of the insulation as a thermal barrier.

GROUND TEMPERATURE VARIABLES AND THEIR INTERACTION

Given a set of soil, moisture, and exposure conditions, the analysis of ground temperatures involves five major variables. The independent variable is temperature and the dependent variables are those of position (transverse, longitudinal, and depth), and time.

Most of the data plots in this report are two-dimensional. However, to aid the reader in understanding the interaction of the variables, limited, three-dimensional plots are shown in Figures 7, 8, 9 and 10. Figure 7 is a plot of measured temperature vs. both time and distance from centerline for two different elevations in Section C. Note that the temperature scale has been offset to prevent overlap of the two surfaces, and that the upper surface is for the lower of the two elevations in the soil profile. It should also be pointed out that for a given elevation the depth of soil over the thermistors decreases as the distance from the centerline increases, because of the normal cross-slope of the pavement and shoulder.

Figure 8 is a plot of measured temperature vs. both time and depth for the centerline of Section B. The effect of the insulation shows up rather markedly in this figure.

Figure 9 is a plot of measured temperature vs. both time and distance from the centerline for similar depths in Sections B and C. Again the temperature scale has been offset to prevent overlap of the two surfaces. The insulating effect is again readily apparent, even after allowance has been made for the offset scale. The separation of the surfaces would be even greater if the depth below the pavement surface was the same for both sections. The depth below the pavement surface is approximately 5 inches greater in Section C, and therefore the temperatures in Section C are warmer than they would have been had they been measured at the same depth as in Section B. In addition, some of the separation of the two surfaces can be attributed to the different soil types in the two sections. The A-4 soil in Section B

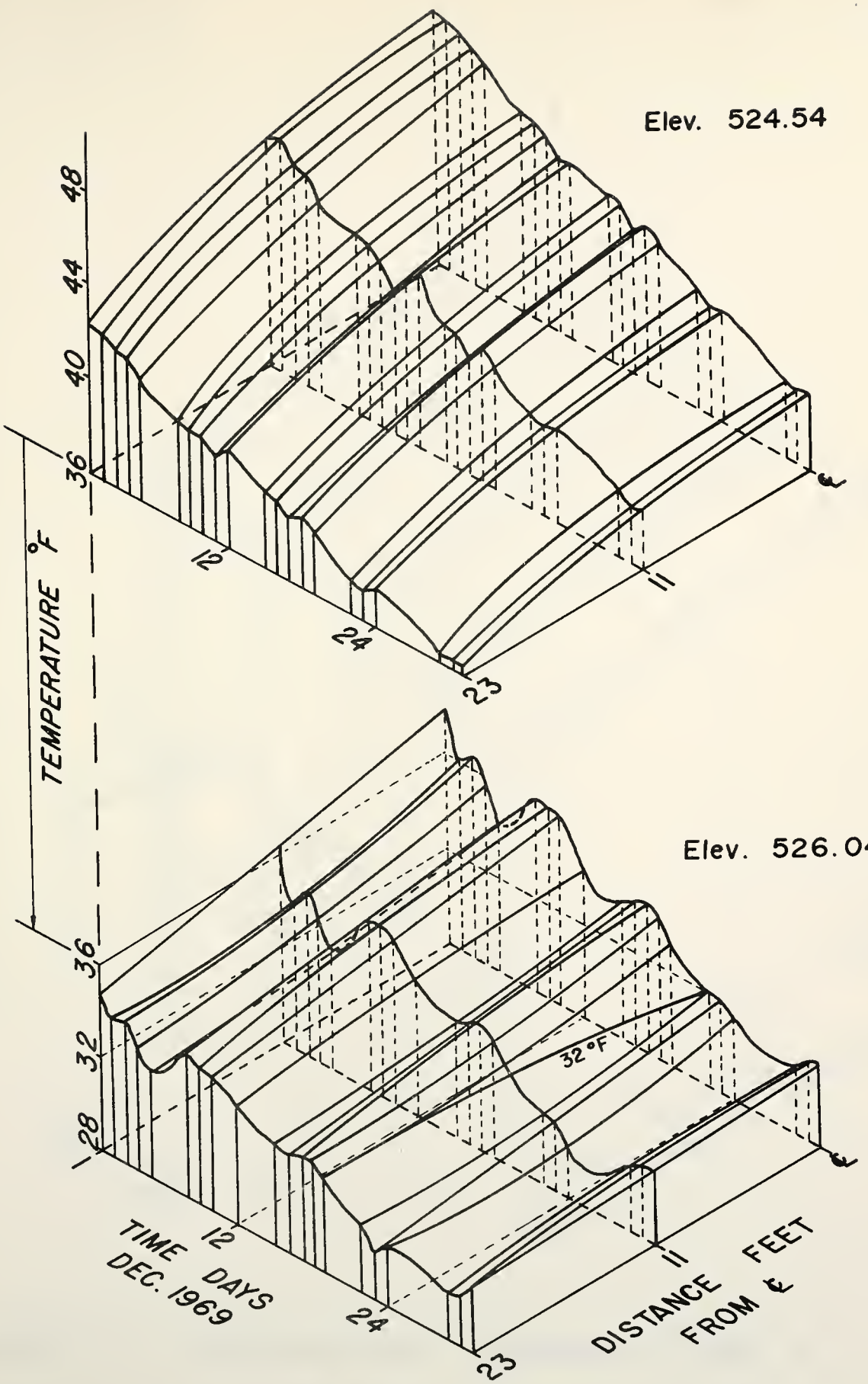


FIGURE 7- TEMPERATURE SURFACES
SECTION C

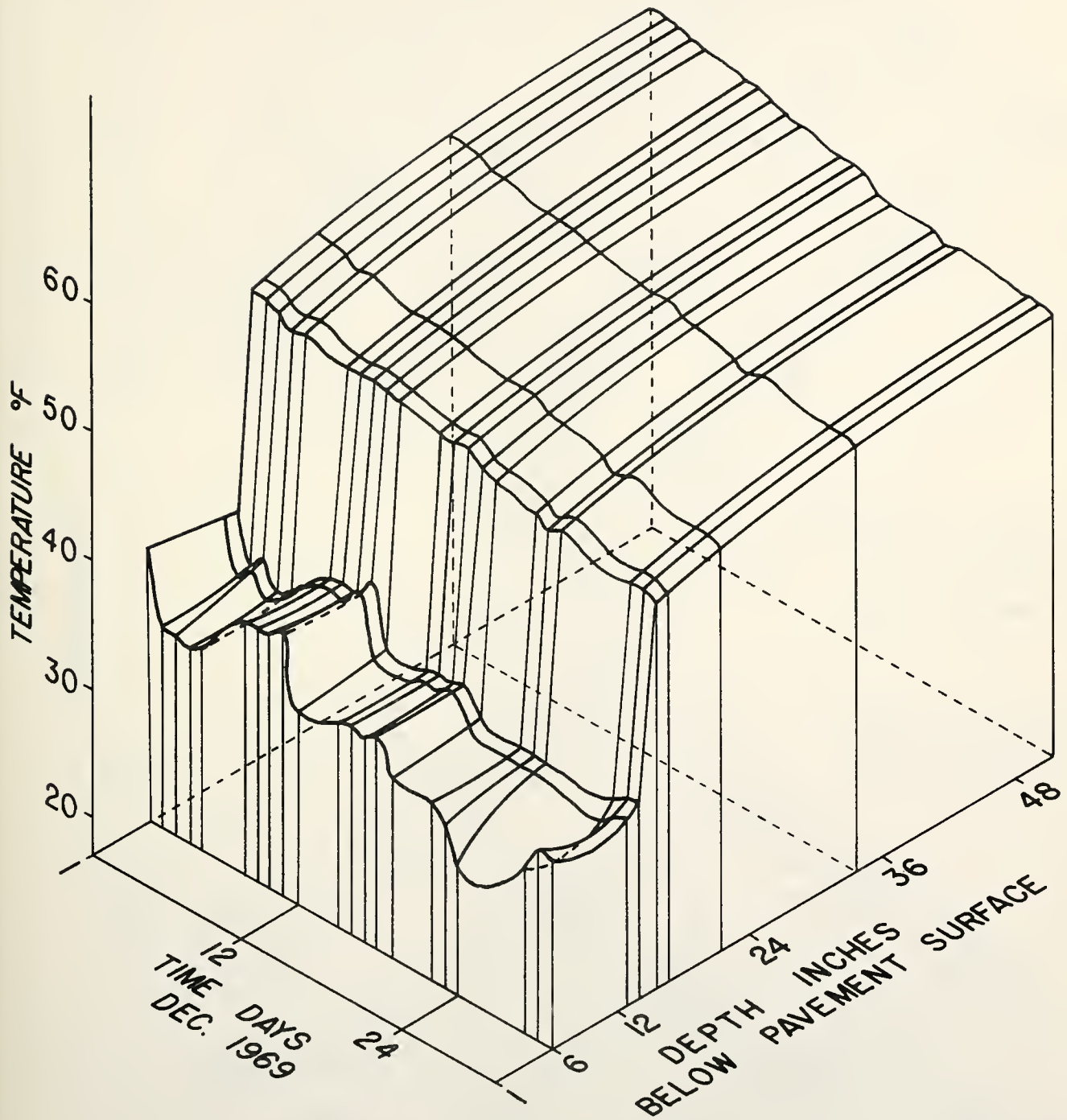


FIGURE 8 - TEMPERATURE SURFACE SEC. B

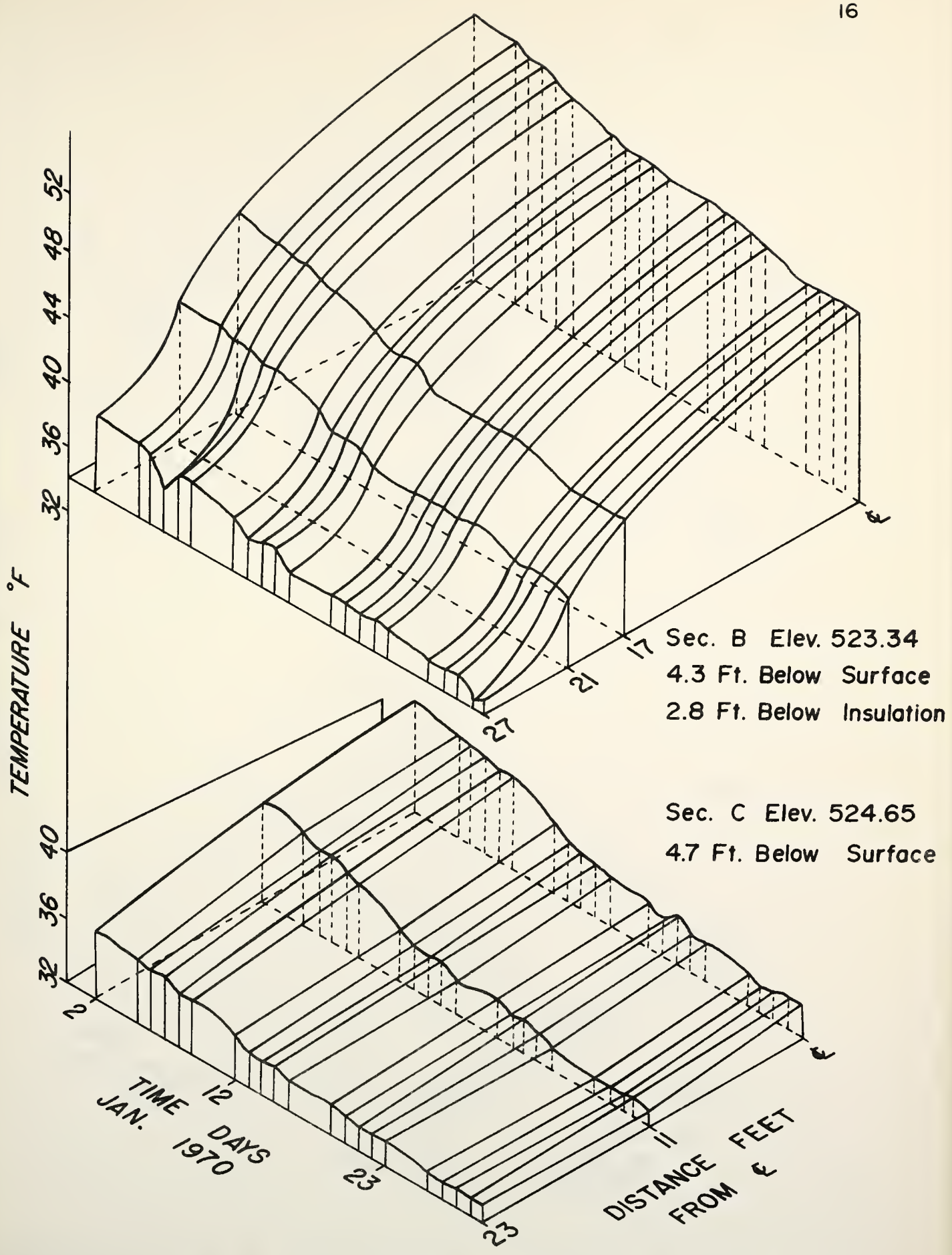


FIGURE 9 - TEMPERATURE SURFACES SEC. B & C

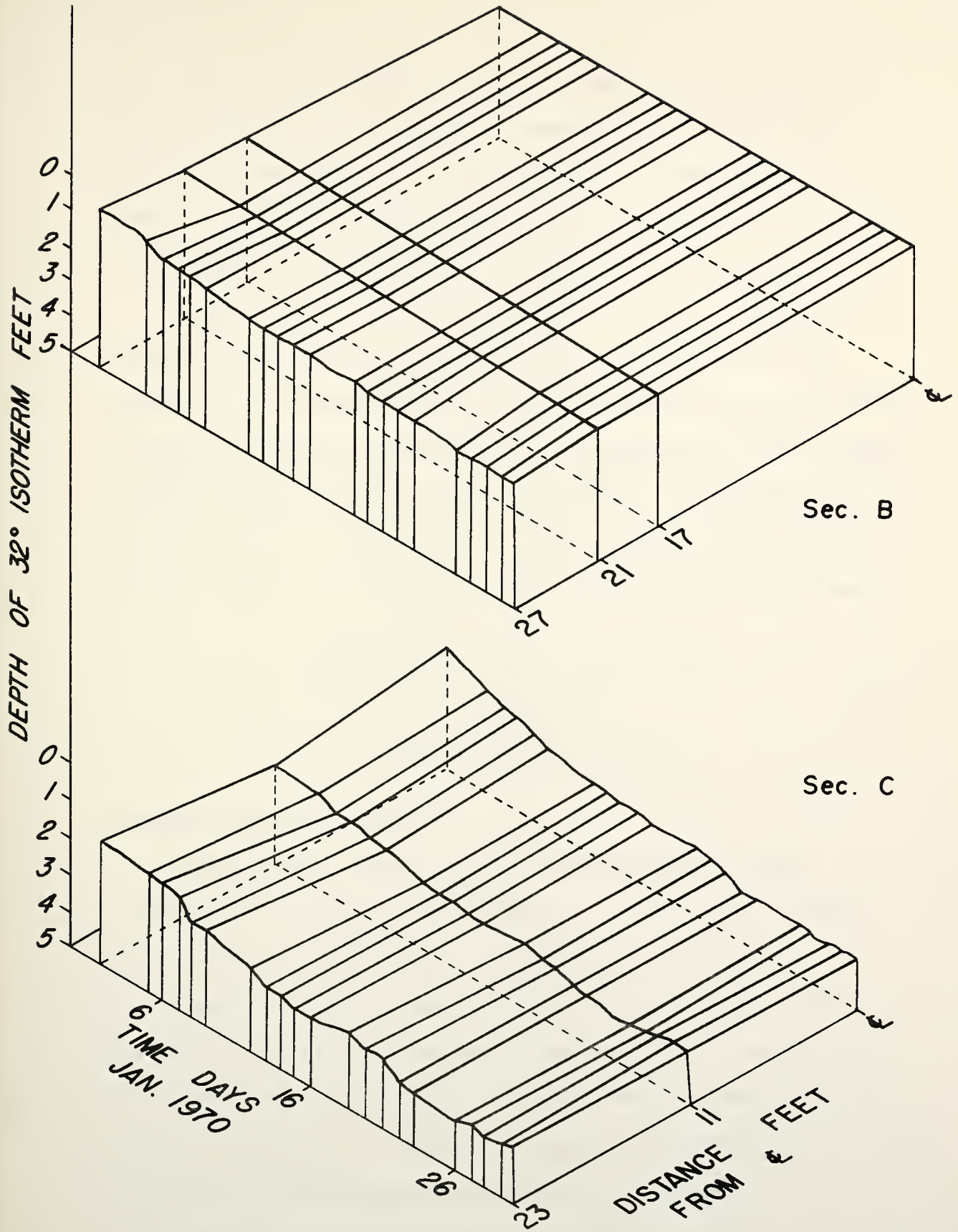


FIGURE 10 - 32 °F ISOTHERM SURFACES, SEC. B & C

has a higher specific heat and a lower thermal conductivity than the A-1-b soil of Section C. Thus the temperature in Section B would tend to be higher than in Section A even if the insulation were not present. Had the temperature surface for Section A been plotted, for a corresponding depth, it would lie between the two surfaces shown.

Figure 10 is a plot of depth of 32°F isotherm vs. both time and distance from centerline for Sections B and C. The surface for Section A would appear similar to that for Section B, since, with the exception of points near the edge of the insulation, the 32°F isotherm did not significantly penetrate the insulation in either section. The depth of the 32°F isotherm would be about 6 inches greater in Section A than in Section B due to the presence of the subbase in Section A.

RELATIVE PERFORMANCE OF THE SECTIONS AS INDICATED BY GROUND TEMPERATURE DATA

Temperature-Time Comparisons

Numerous temperature vs. time plots, representing traces on surfaces such as those shown in Figures 7, 8 and 9, can be drawn if the position variables are held constant for each trace.

Figure 11 shows temperature vs. time plots at the centerline of the three sections for approximately the same depth in each section. The effect of the insulation in Sections A and B is readily apparent. Also the insulation in Section B is obviously more effective than that in Section A, even though the insulation in Section B has 6 inches less cover. The 1/2 inch increase in thickness and the 12 foot increase

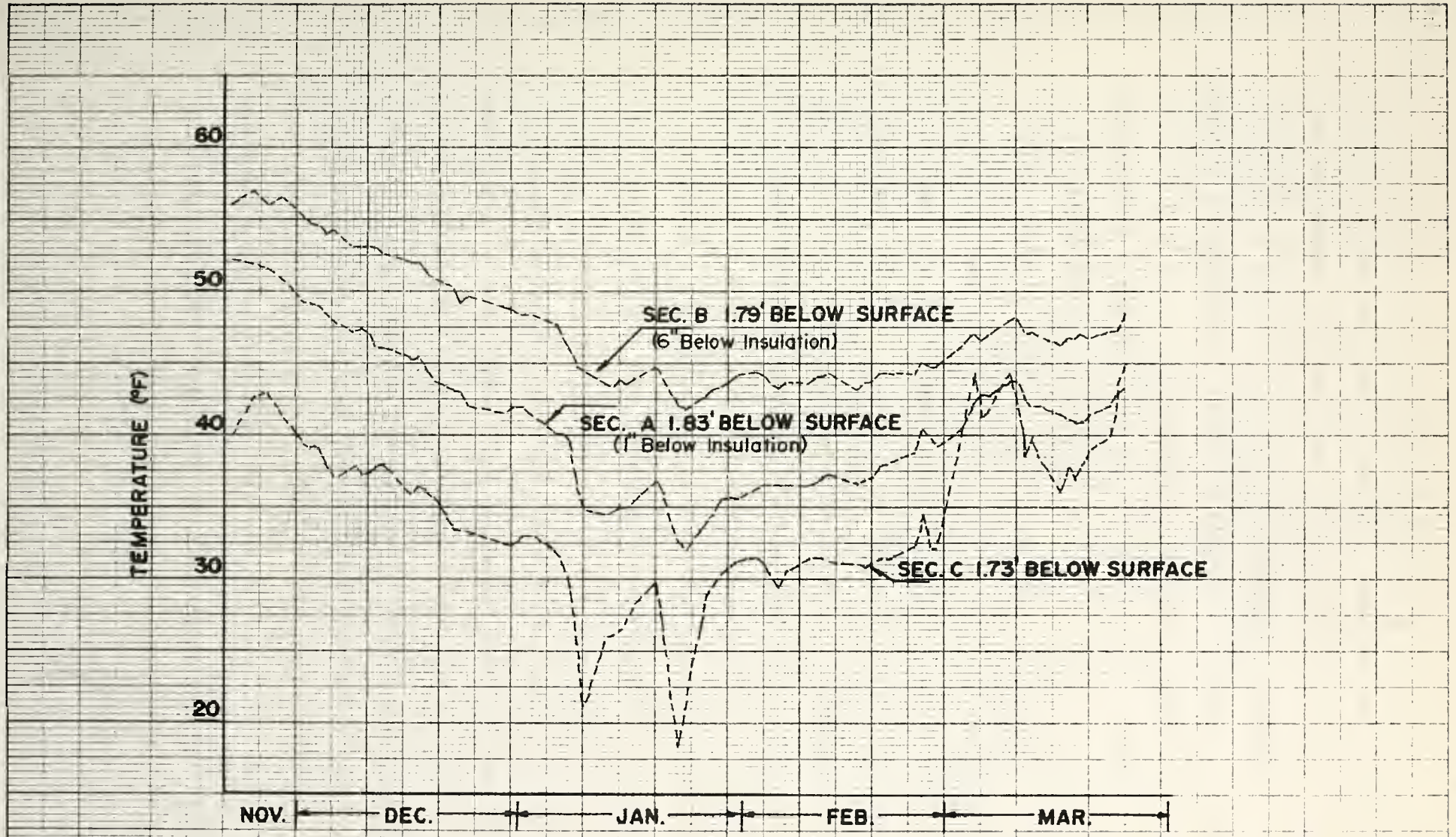


FIGURE 11- TEMPERATURE vs. TIME
CENTERLINE
1969-70

in width of the insulation in Section B more than compensates for the reduction in the depth of cover. Note that for Section A the temperature on January 23 was 31.8°F, indicating that frost penetration into the subgrade was imminent. However, a significant change in cooling rate occurred at that time, as indicated on the degree-day curve in Figure 6, resulting in a trend of increasing temperature at that point during the remainder of the season.

The fact that freezing temperatures may have penetrated the insulation in Section A would lead one to question the adequacy of the design, since the freezing index for 1969-70 was only 673 degree-days vs. 1274 degree-days for the design year. However, if one refers to the predicted temperatures on the centerline and one inch below the insulation, which are shown in Figures 10 and 11 of Stulgis' report [4], it will be seen that for the design year the temperature is below freezing for approximately one and one-half months in Section A and for two periods (the longest being approximately 14 days) in Section B. Furthermore, for the design year, the date on which freezing temperatures are predicted to penetrate the insulation in Section A is January 22. If one refers to the degree-day curve for the design year (Figure 6, Stulgis [4]) the cumulative degree-days of cooling on January 22 is 580, whereas for the 1969-70 season, and for freezing temperatures penetrating the insulation on January 23, the cumulative degree-days of cooling is 540. Thus the section is apparently performing about as predicted.

Figure 12 shows temperature vs. time curves for the deepest thermistors on the centerline of the three sections. The effect of the

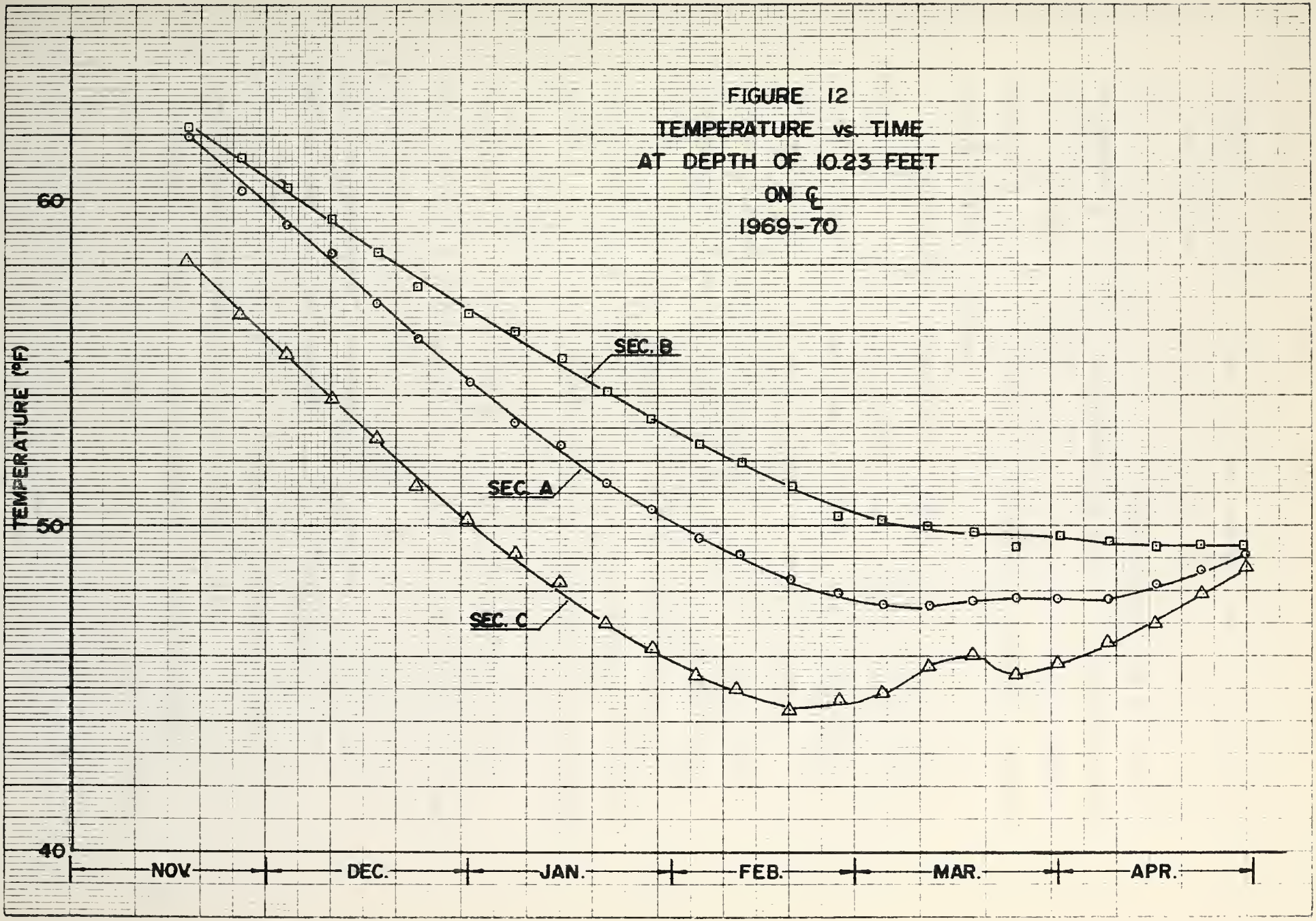


FIGURE 12
TEMPERATURE vs. TIME
AT DEPTH OF 10.23 FEET
ON ℄
1969-70
TEMPERATURE (°F)
60
50
40
SEC. B
SEC. A
SEC. C
NOV.
DEC.
JAN.
FEB.
MAR.
APR.

insulation is quite marked; with the maximum temperature difference between Sections A and C being about $4^{\circ}F$, and between B and C about $7^{\circ}F$. However, the difference in the thermal properties of the soils in Section B and those in Sections A and C would contribute to some of the separation between the curve for Section B and the curves for Sections A and C. These curves are discussed further in the section on temperature prediction.

Figure 13 shows temperature vs. time curves on the centerline and 6 inches below the insulation for both insulated sections. The curves are reasonably smooth due to the fact that average weekly temperatures have been plotted instead of daily temperatures. The distance between the curves represents, primarily, the additional effectiveness of the insulation in Section B over that in Section A.

The difference in temperatures at a given depth below the insulation decreases out near the edge of the insulation as shown in Figure 14. At 1 inch below and 2 feet from the edge of the insulation the temperatures in Section B are generally warmer than those in Section A, but the difference is not as large as at the centerline. The reason for the reduced separation of the curves in Figure 14 over that of the curves in Figure 13 is that the point 1 inch below and 2 feet from the edge of the insulation in Section B is much closer to the shoulder and slope surfaces than the corresponding point in Section A (see Figures 3 and 4). Thus the insulating effect of the overlying soil is significantly less in Section B.

Figures 15, 16 and 17 are temperature vs. time plots for, in most cases, the deepest thermistors in each section. These plots were

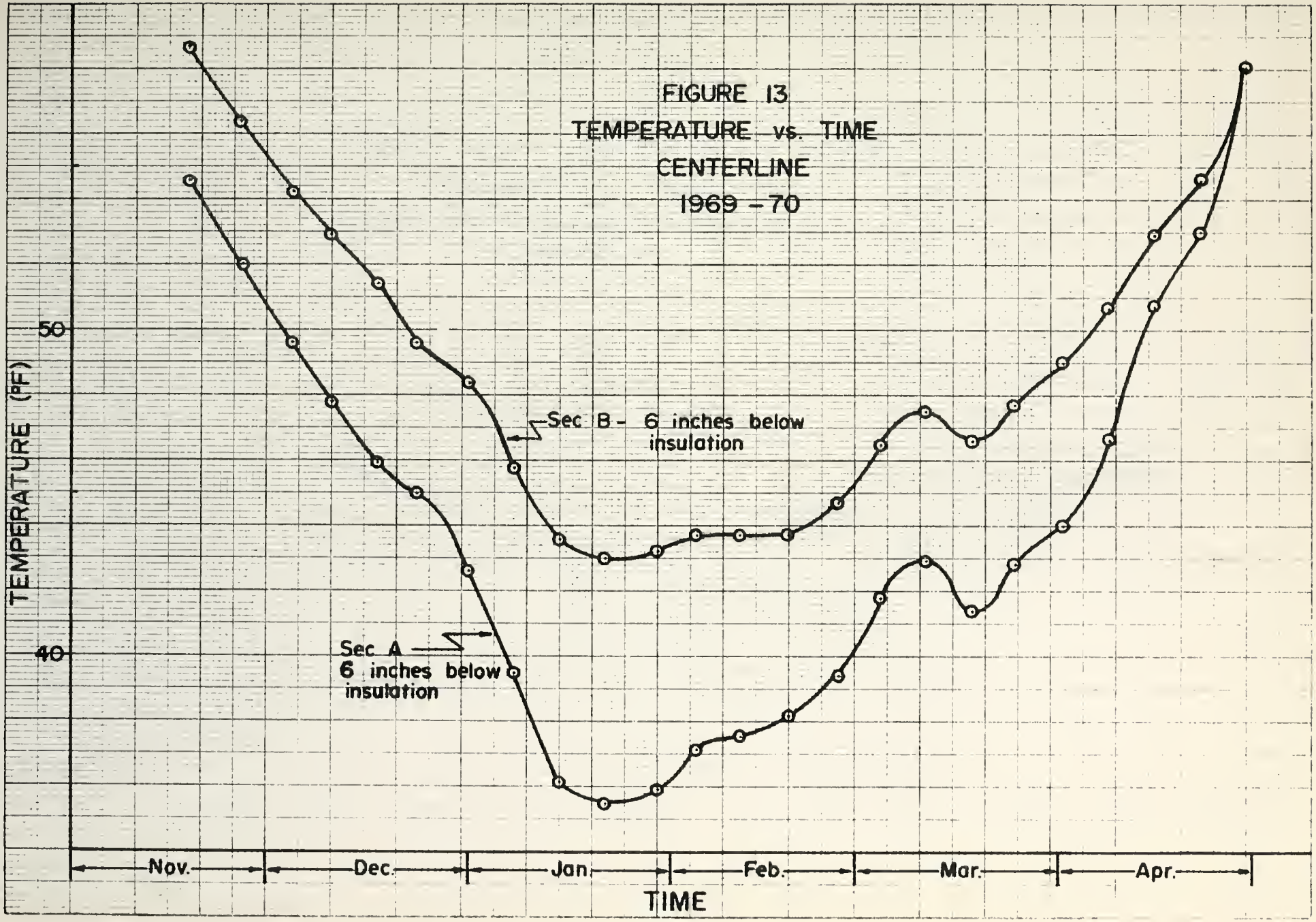


FIGURE 13
TEMPERATURE vs. TIME
CENTERLINE
1969 - 70
TEMPERATURE (°F)
50
40
Sec B - 6 inches below insulation
Sec A
6 inches below insulation
Nov.
Dec.
Jan
Feb.
Mar.
Apr.
TIME

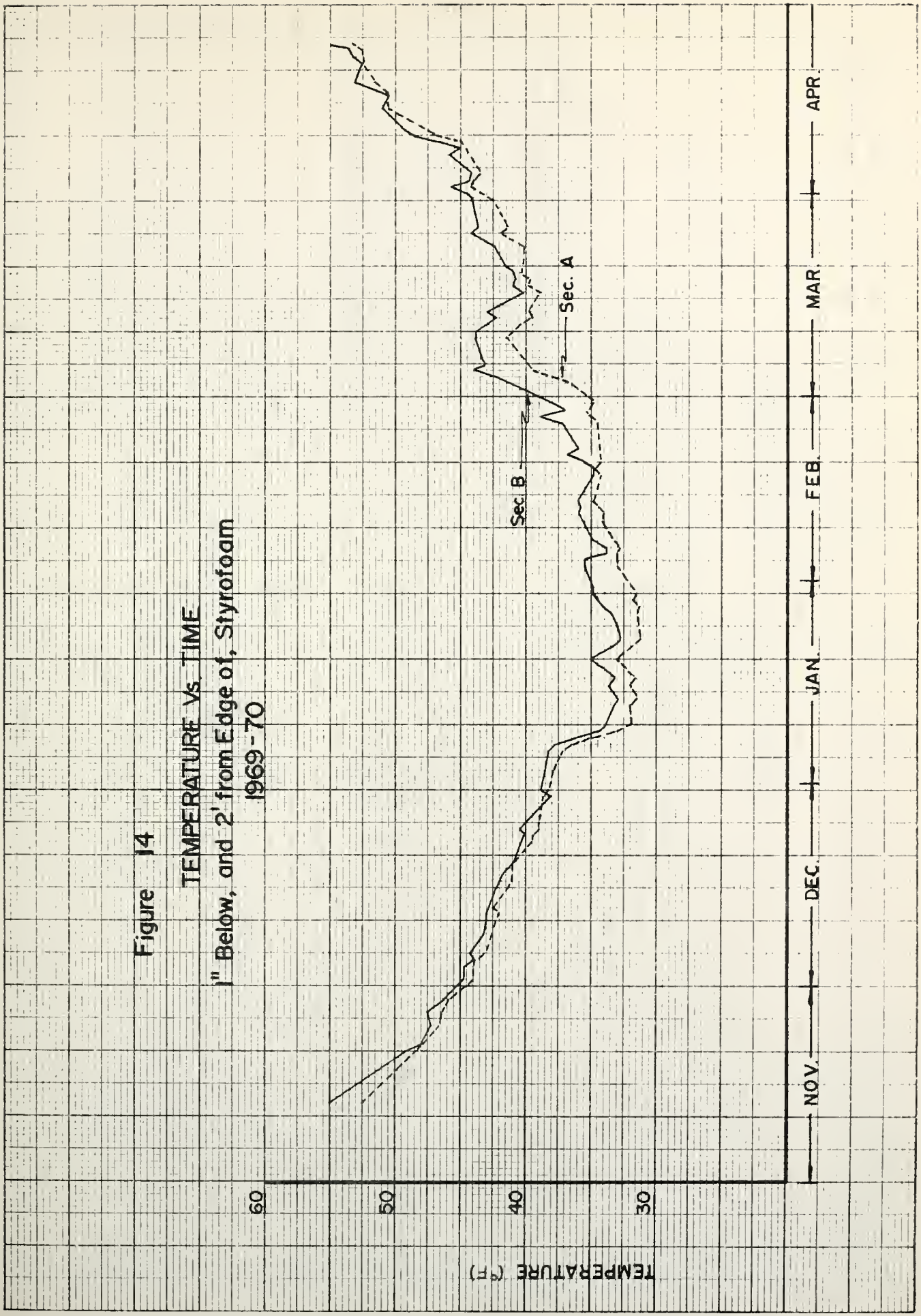


Figure 14

TEMPERATURE Vs. TIME

1" Below, and 2' from Edge of, Styrofoam

1969-70

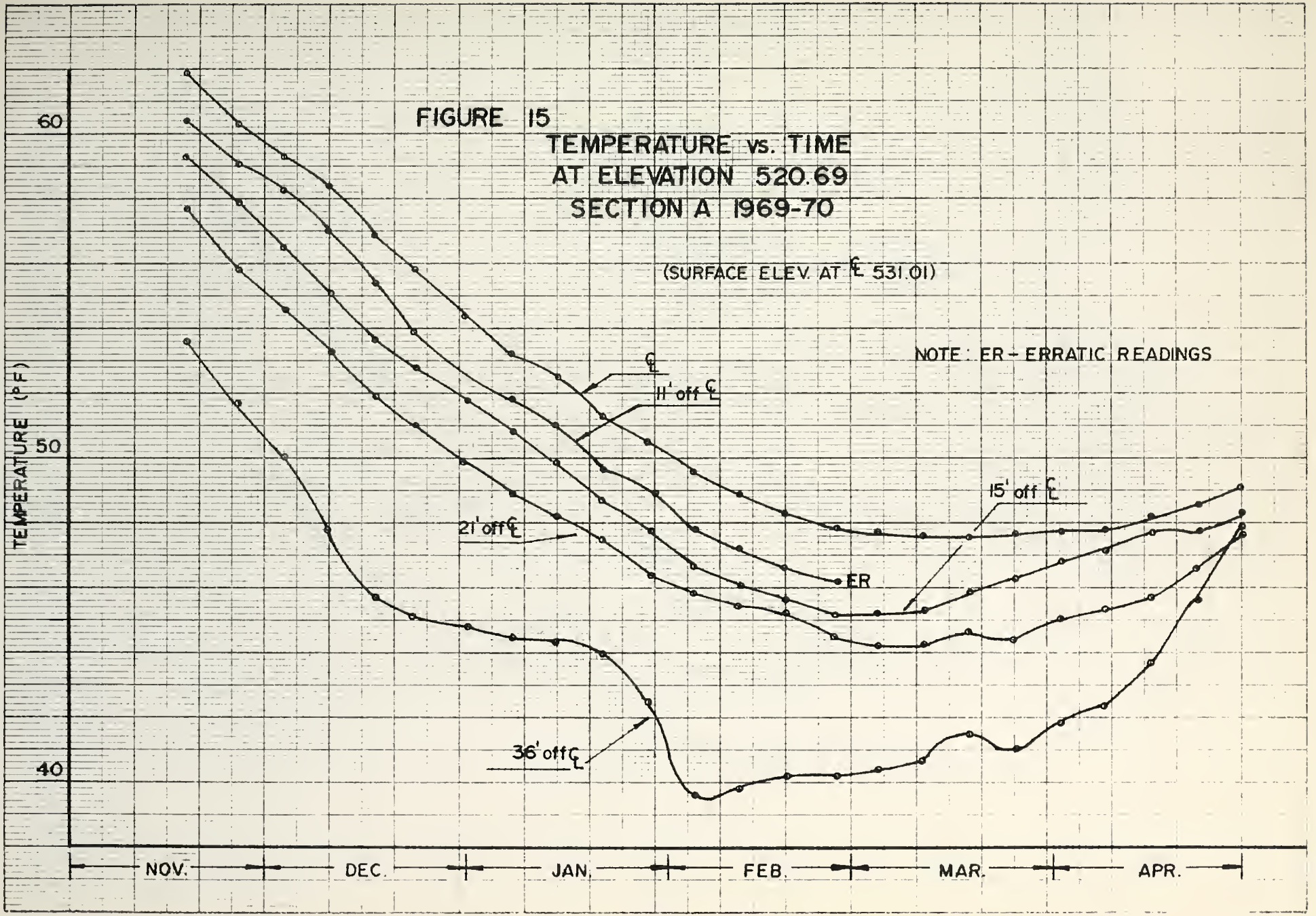


FIGURE 15
TEMPERATURE vs. TIME
AT ELEVATION 520.69
SECTION A 1969-70
(SURFACE ELEV. AT ℄ 531.01)
NOTE: ER - ERRATIC READINGS
TEMPERATURE (°F)
60
50
40
℄
11' off ℄
15' off ℄
21' off ℄
ER
36' off ℄
NOV.
DEC.
JAN.
FEB.
MAR.
APR.

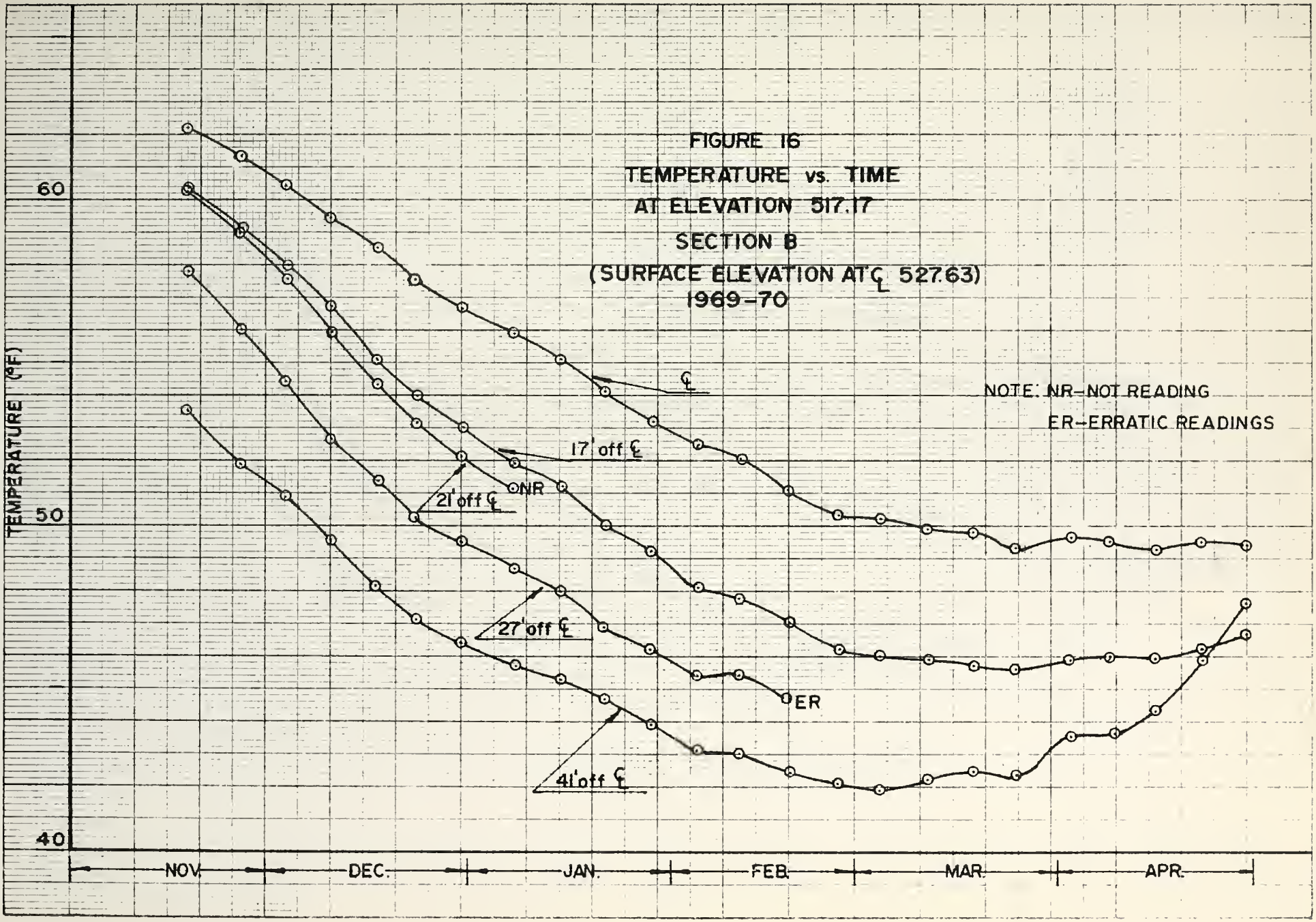


FIGURE 16
TEMPERATURE vs. TIME
AT ELEVATION 517.17
SECTION B
(SURFACE ELEVATION AT ℄ 527.63)
1969-70
TEMPERATURE (°F)
60
50
40
NOV.
DEC.
JAN.
FEB.
MAR.
APR.
℄
17' off ℄
21' off ℄
27' off ℄
41' off ℄
NR
ER
NOTE: NR-NOT READING
ER-ERRATIC READINGS

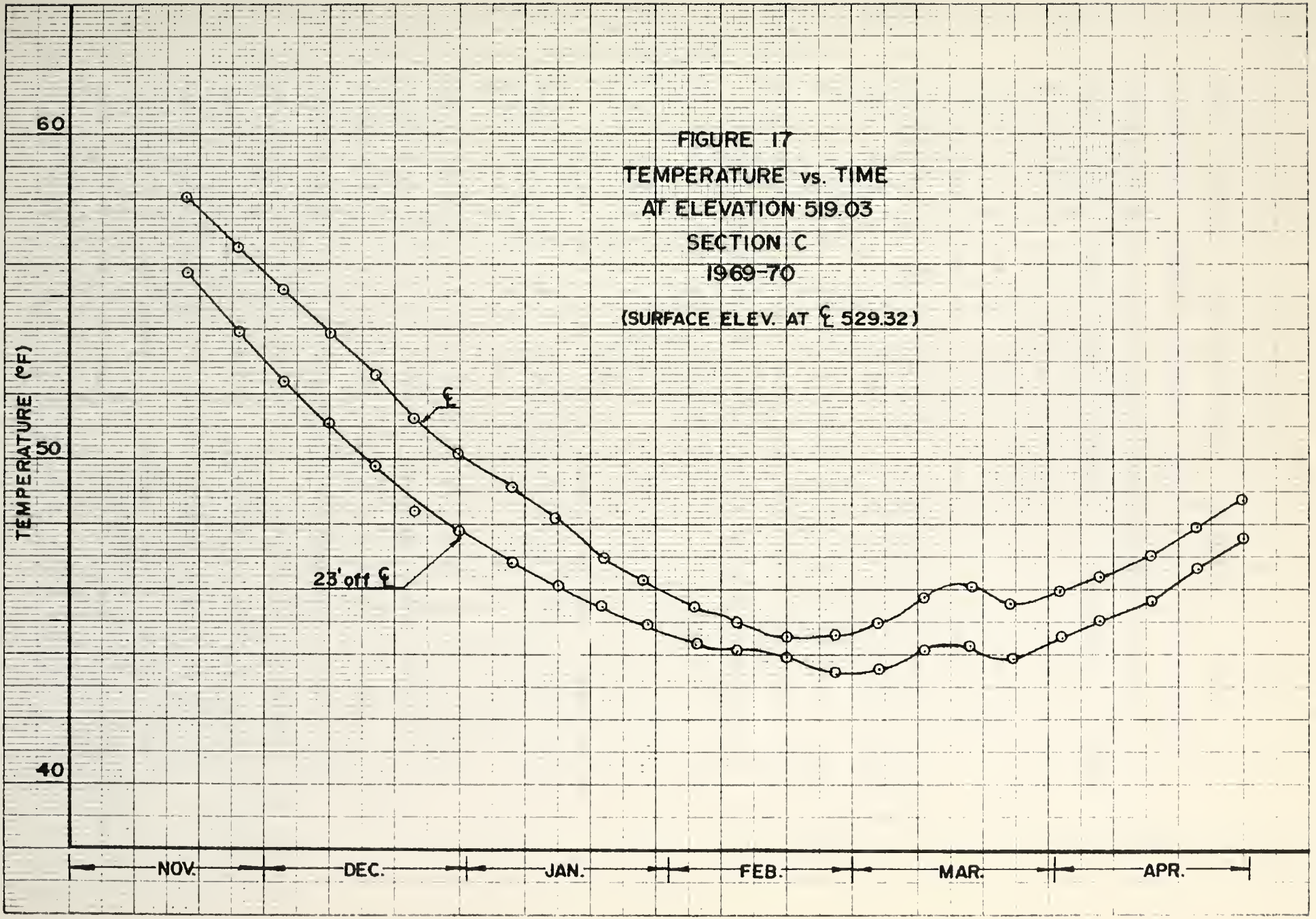


FIGURE 17
TEMPERATURE vs. TIME
AT ELEVATION 519.03
SECTION C
1969-70
(SURFACE ELEV. AT ℄ 529.32)

made to study the lateral variation in temperature at depth for temperature prediction purposes. The curves do show that the insulation significantly increases the lateral variation in temperature for a constant depth below the centerline. The comparison is made on the basis of the difference in temperature between the centerline and the shoulder point (23 feet off centerline), since Section C has no thermistors beyond the shoulder point. Unfortunately the comparison requires an interpolation of temperatures at the shoulder point for Sections A and B due to the fact that the lateral positions of the thermistors do not correspond in the three sections. Since the plots are for a constant depth below centerline, the depth of soil cover decreases as the distance from the centerline increases, especially beyond the shoulder point.

Isotherms for Time = Constant

Figures 18, 19 and 20 show isotherms interpreted from measured temperatures for all three sections on December 24, 1969. Figures 21, 22 and 23 show the same thing for January 20, 1969, close to the day of maximum frost penetration in the control section. For the uninsulated section the isotherms are approximately parallel to the ground surface. This is what would be expected when there is little lateral variation in soil properties and when snow cover is either non-existent or relatively shallow. In areas of heavy snowfall the ground is not likely to freeze much beyond the shoulder point, due to the insulating effect of the snow. If such is the case then the isotherms for temperatures at, or below, freezing will be concave upward, cross the ground surface near the shoulder point, and progress

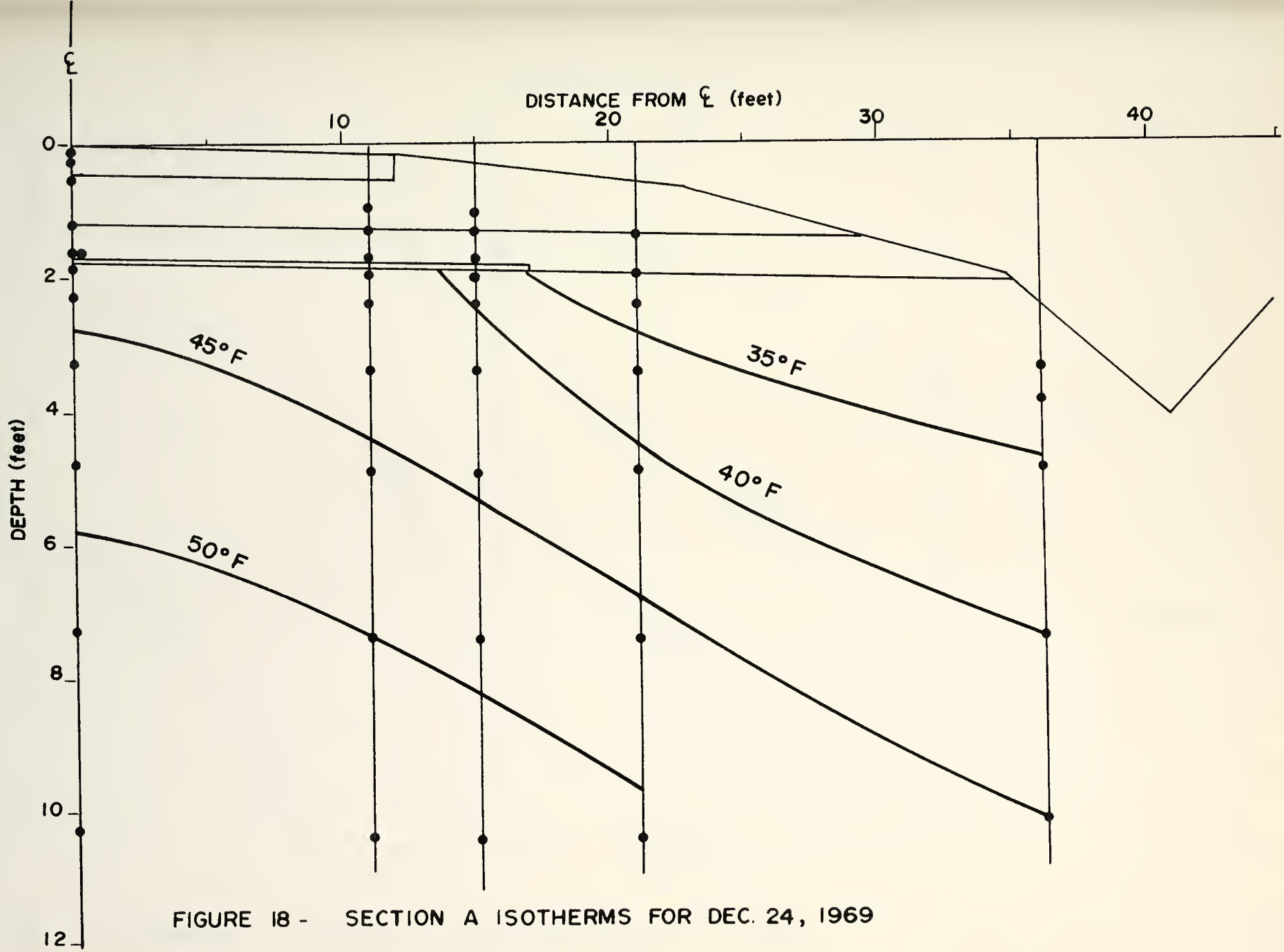


FIGURE 18 - SECTION A ISOTHERMS FOR DEC. 24, 1969

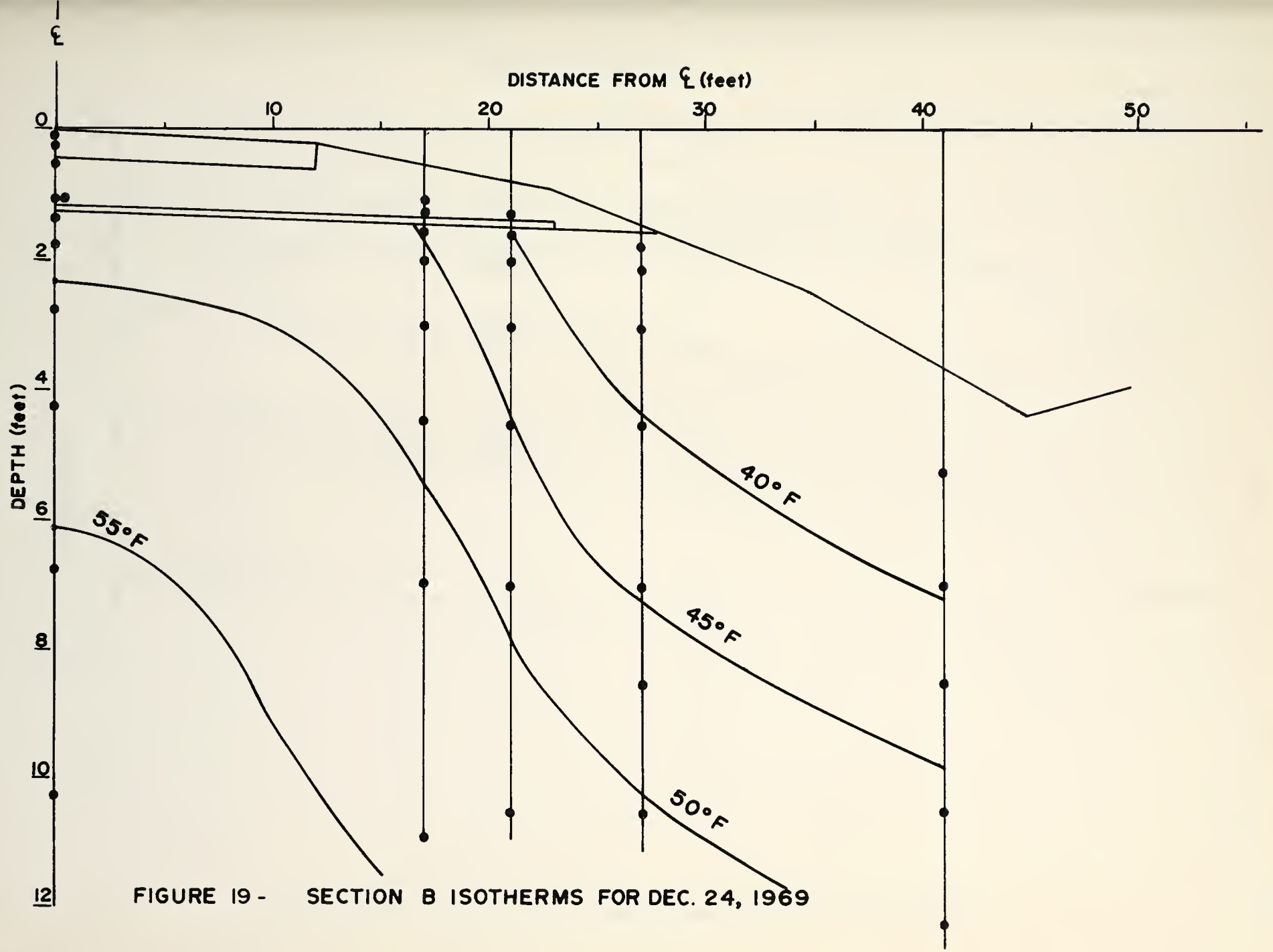


FIGURE 19 - SECTION B ISOTHERMS FOR DEC. 24, 1969

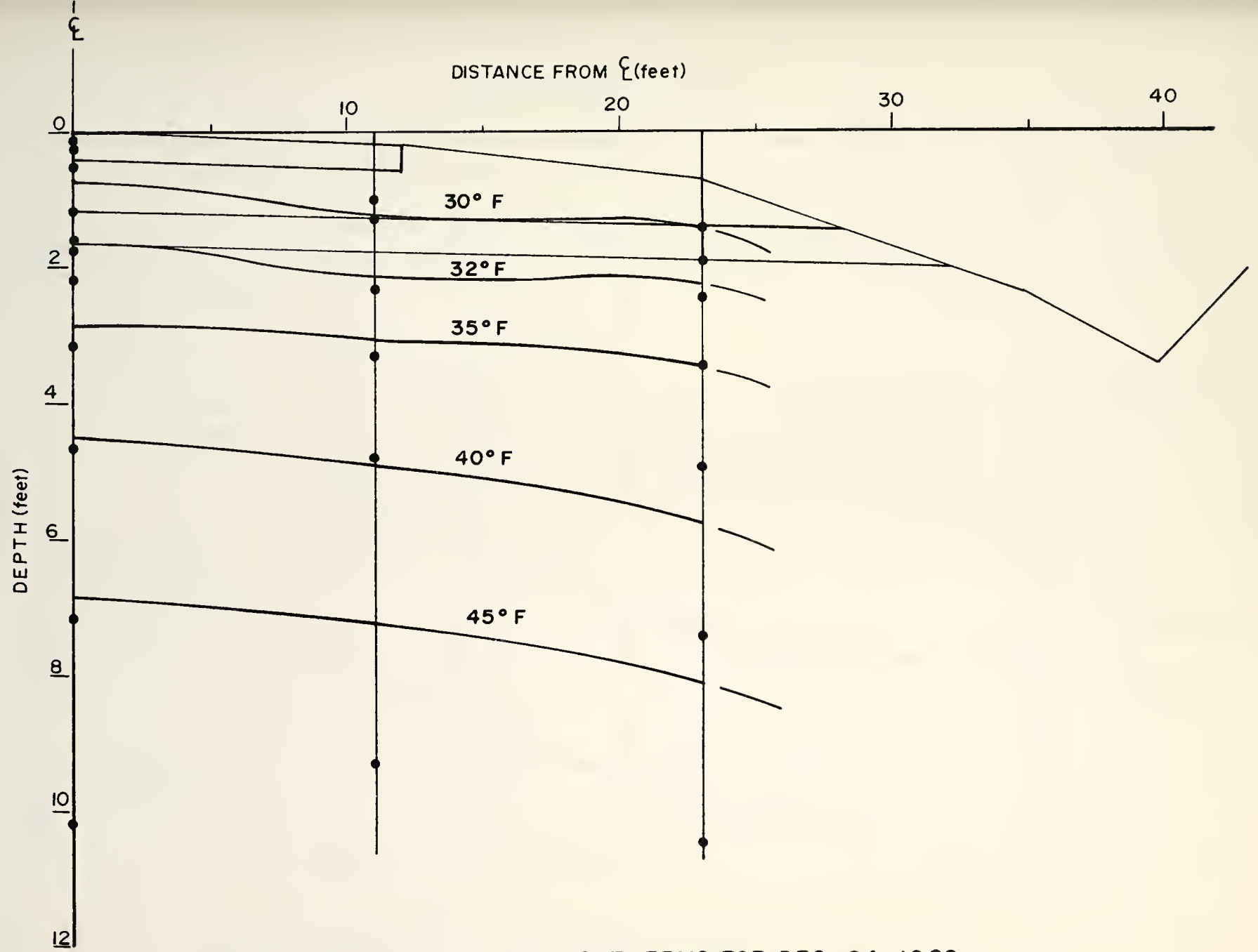


FIGURE 20- SECTION C ISOTHERMS FOR DEC. 24, 1969

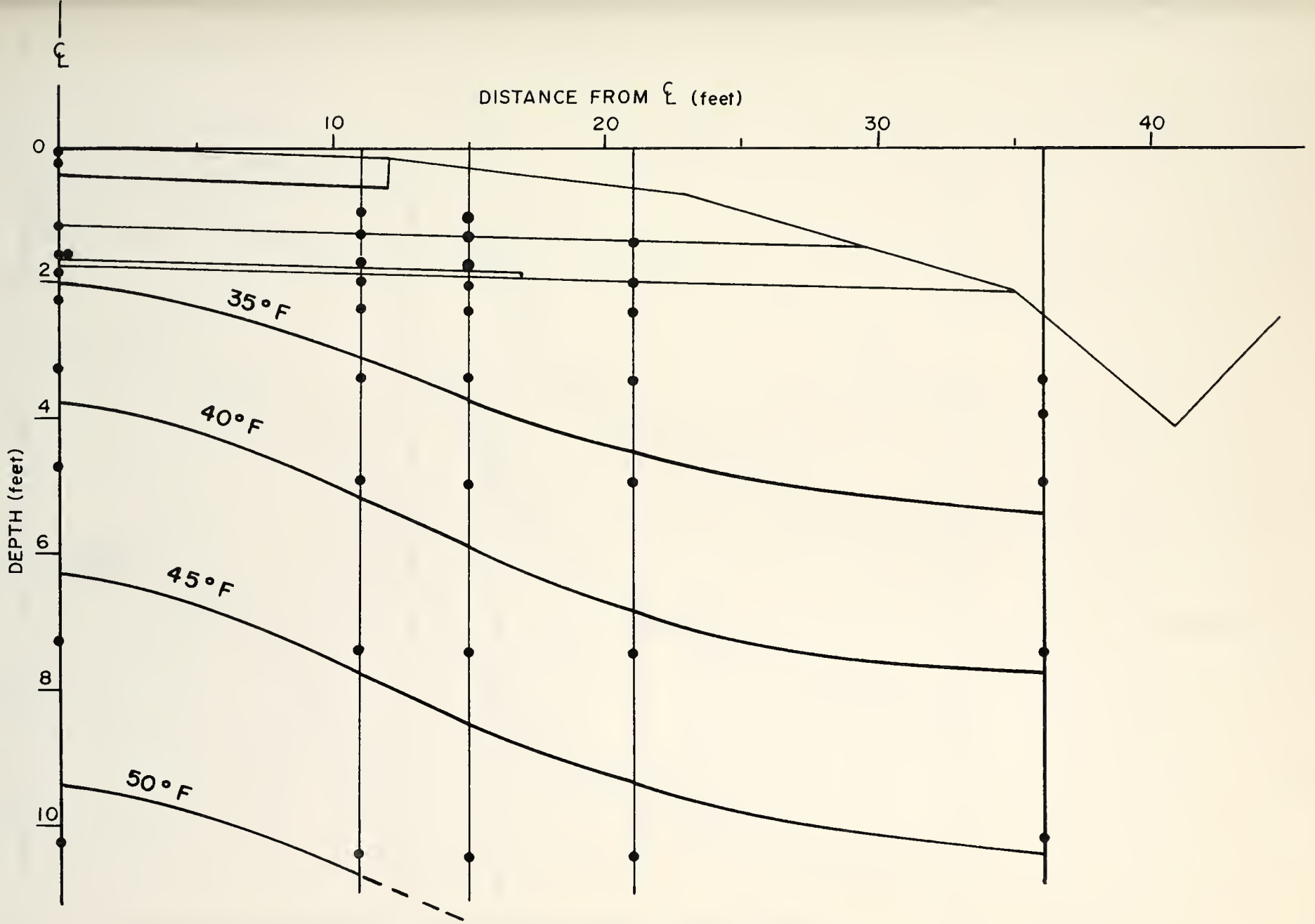


FIGURE 21- SECTION A ISOTHERMS FOR JAN. 20, 1970

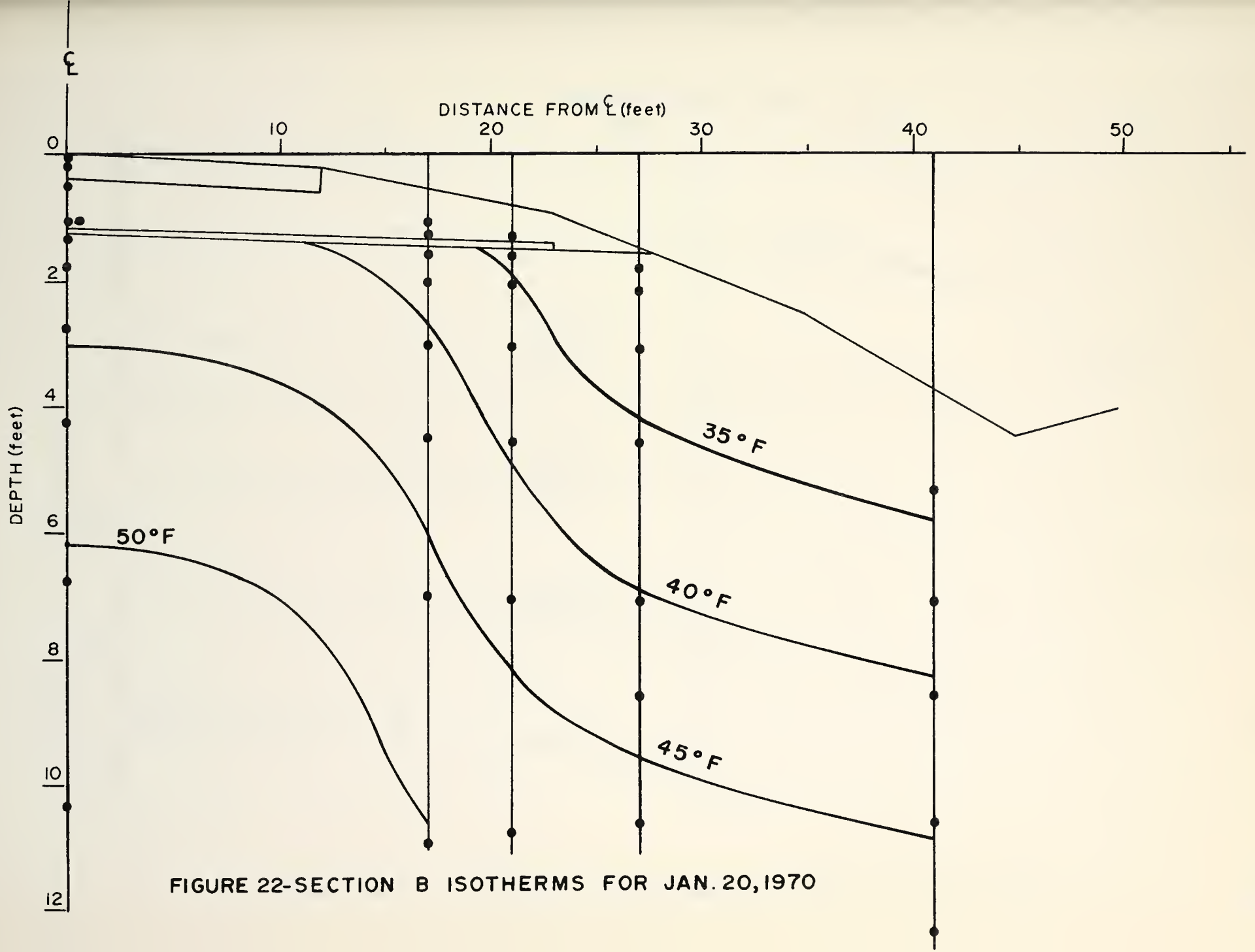


FIGURE 22-SECTION B ISOTHERMS FOR JAN. 20, 1970

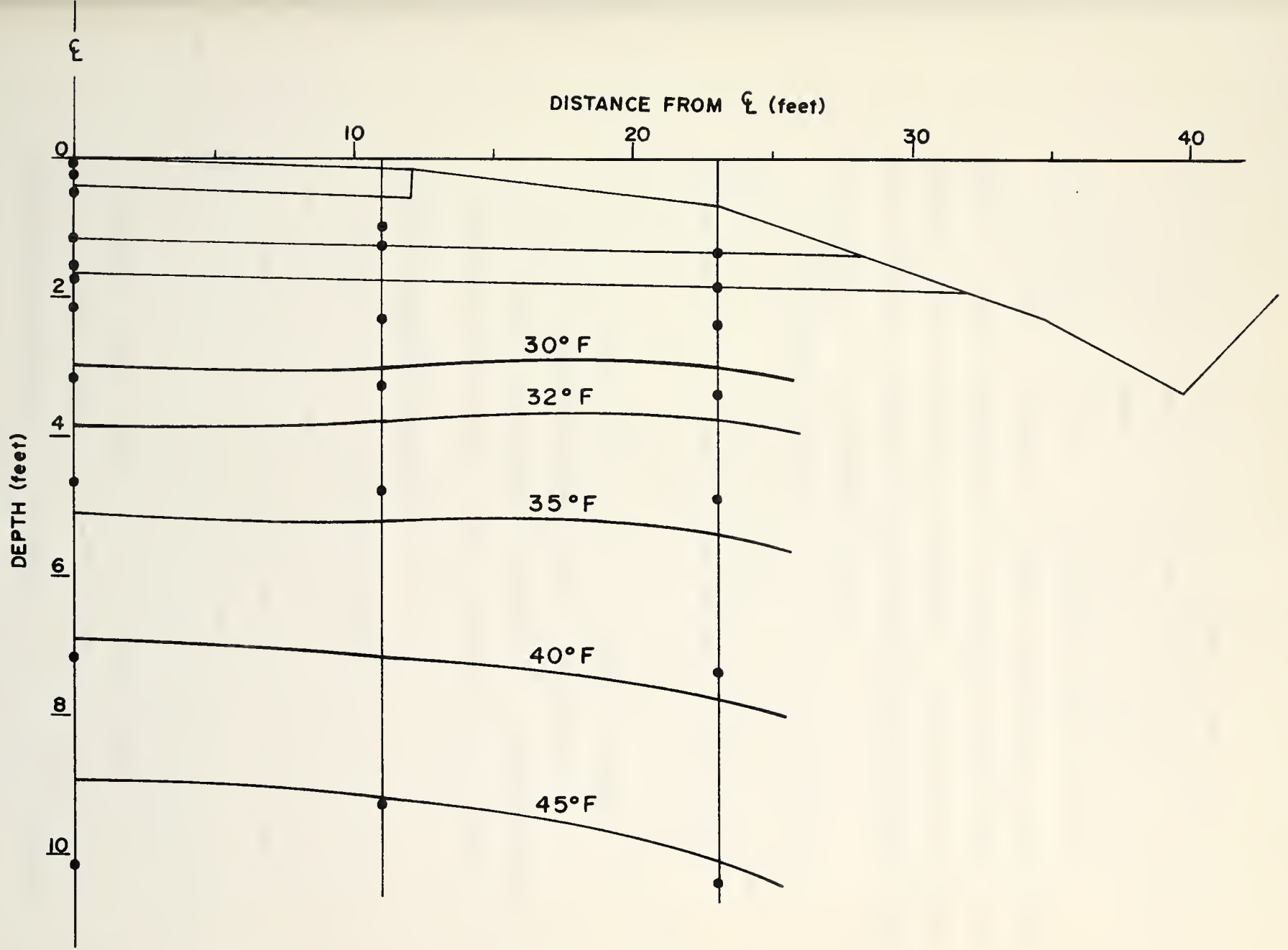


FIGURE 23 - SECTION C ISOTHERMS FOR JAN. 20, 1970

through the snow cover approximately parallel to the surface of the snow. For insulated sections in areas of heavy snowfall the shape of the isotherms will depend on the width of the insulation and the relative insulating effects of the insulation and the snow cover.

The presence of insulation in Sections A and B does significantly modify the shape and magnitude of the isotherm at a given depth, with the effect being the greatest for Section B. Note that the horizontal scale for Section B differs from that for the other two sections, thus the figures are not all directly comparable.

The interpolated temperature at a point directly beneath the insulation and at the edge of the pavement for January 20 is about $40^{\circ}F$ for Section B and about $33^{\circ}F$ for Section C. Thus freezing temperatures are about to penetrate the subgrade at the pavement edge in Section A, whereas Section B, at the corresponding point, still has a fairly adequate temperature margin above freezing.

The increase in the range of temperatures at a given depth due to the presence of the insulation shows up markedly in these figures.

Centerline Temperature Gradients

A common method of illustrating the effect of the insulation is to plot temperature gradients (temperature vs. depth curves). Curves of this type represent traces in surfaces such as the one shown in Figure 8, if time is held constant for each trace.

Figure 24 shows the centerline gradients for all three sections on December 24, 1969, shortly after the freezing season began. Figure 25 shows the same thing for January 22, 1970, near the day of maximum frost penetration in the control section. The effect of the

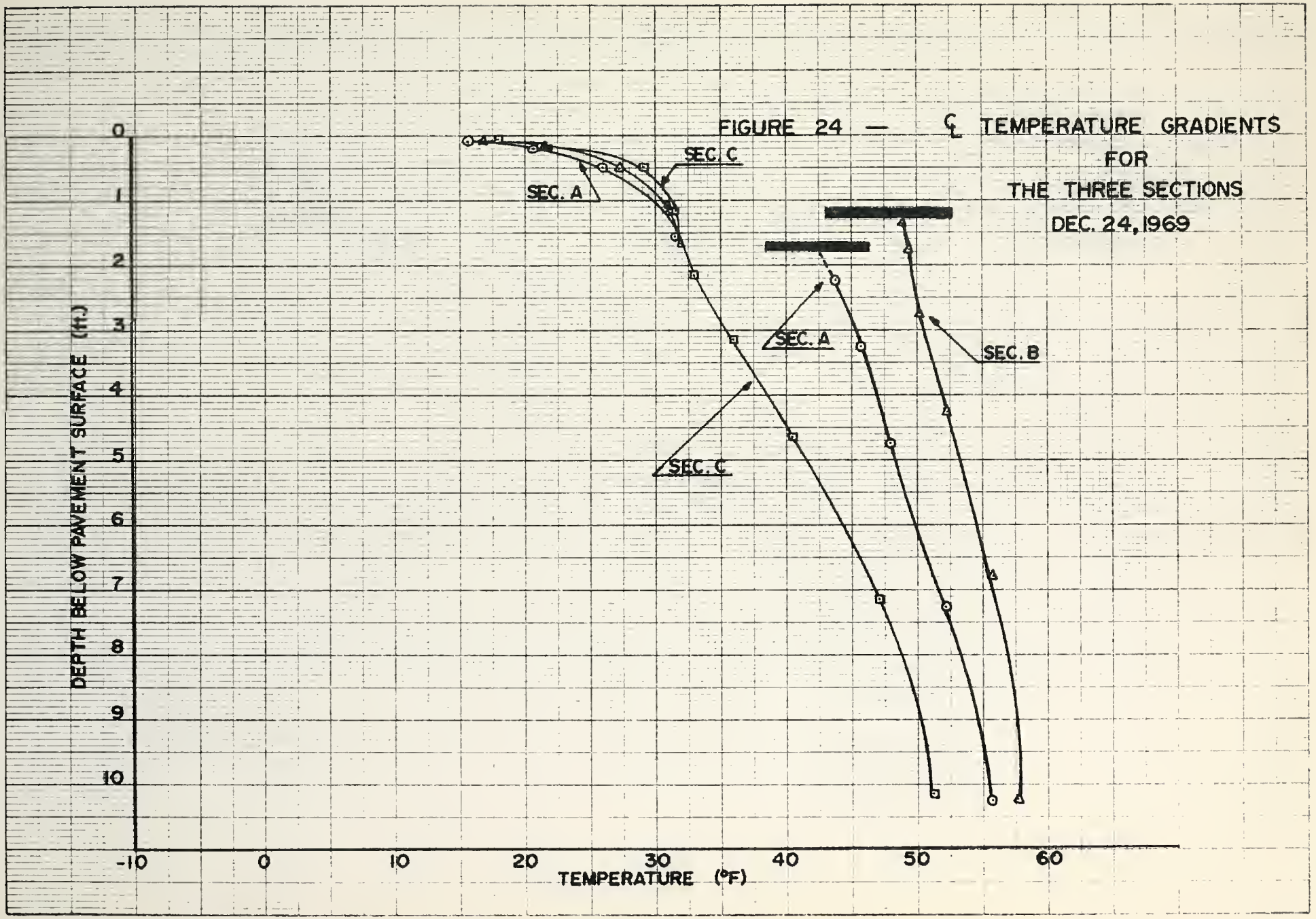


FIGURE 24 — ℄ TEMPERATURE GRADIENTS FOR THE THREE SECTIONS DEC. 24, 1969
SEC. A
SEC. C
SEC. A
SEC. B
SEC. C
DEPTH BELOW PAVEMENT SURFACE (ft.)
0
1
2
3
4
5
6
7
8
9
10
-10
0
10
20
30
40
50
60
TEMPERATURE (°F)

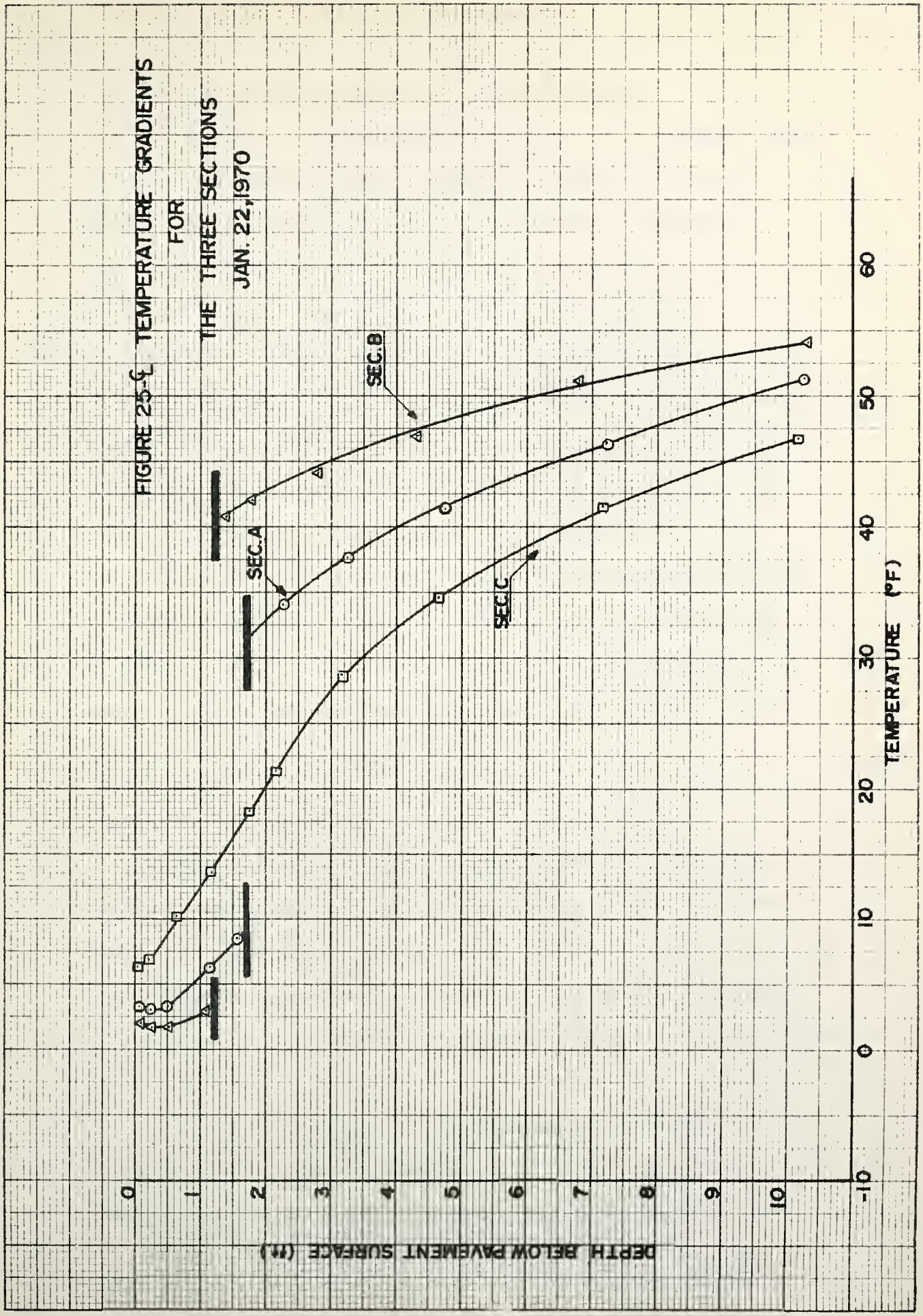


FIGURE 25-C TEMPERATURE GRADIENTS FOR THE THREE SECTIONS JAN. 22, 1970
SEC.B
SEC.A
SEC.C
DEPTH BELOW PAVEMENT SURFACE (ft)
TEMPERATURE (°F)
0
1
2
3
4
5
6
7
8
9
10
-10
0
10
20
30
40
50
60

insulation is clearly illustrated in these figures.

Figure 25 shows that freezing temperatures have reached a depth of 4 feet (2.23 feet below the subgrade surface) in the control section, and that freezing below the insulation is imminent in Section A. In Section B the temperature at the surface of the subgrade is about 8 degrees above freezing. Also shown in Figure 25 is the fact that road surface temperatures in the three sections may differ considerably, which suggests that under surface icing conditions the time at which ice forms, or melts, may be different for the three sections. The possibility of differential icing occuring on the sections is examined in a later section of the report.

Figure 26 shows centerline temperature gradients for April 22, 1970, after the spring warming trend has been in effect for some time. Illustrated in the figure is the fact that the uninsulated section warms up faster than the insulated sections, and that the heavier insulated section is the slowest to warm up.

Depth of Frost Penetration

Figures 27, 28 and 29 show the depth of the 32°F isotherm (nominal frost depth) vs. time for the three sections. The plots are for the centerline of each section. Points plotted at the top of the insulation simply indicate that the 32°F isotherm was somewhere in the insulation, in which case no attempt was made to establish its exact position.

As previously mentioned, freezing temperatures may have penetrated the insulation in Section A on January 23, since the temperature 1 inch below the insulation was 31.8°F on that day.

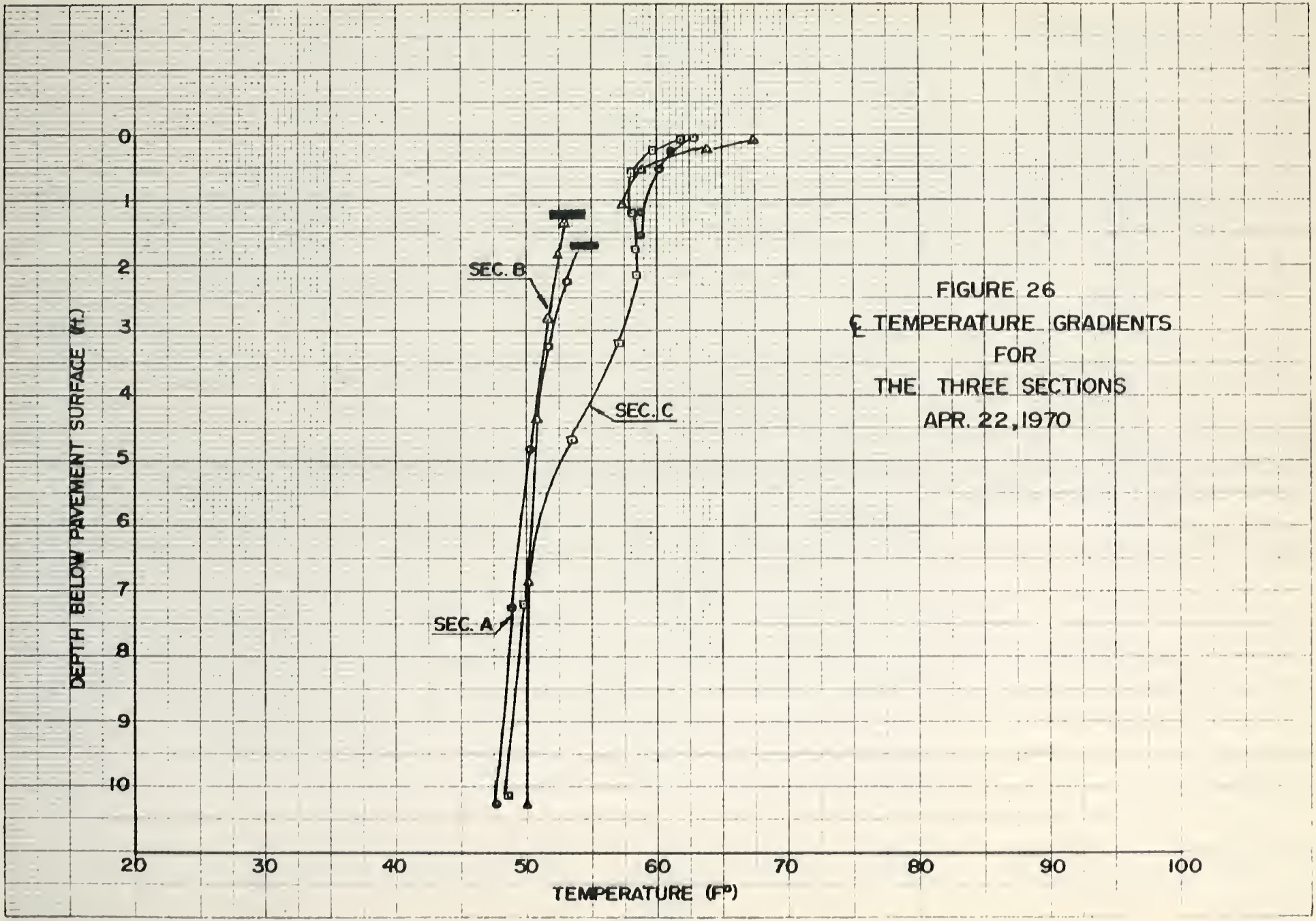


FIGURE 26
TEMPERATURE GRADIENTS
FOR
THE THREE SECTIONS
APR. 22, 1970

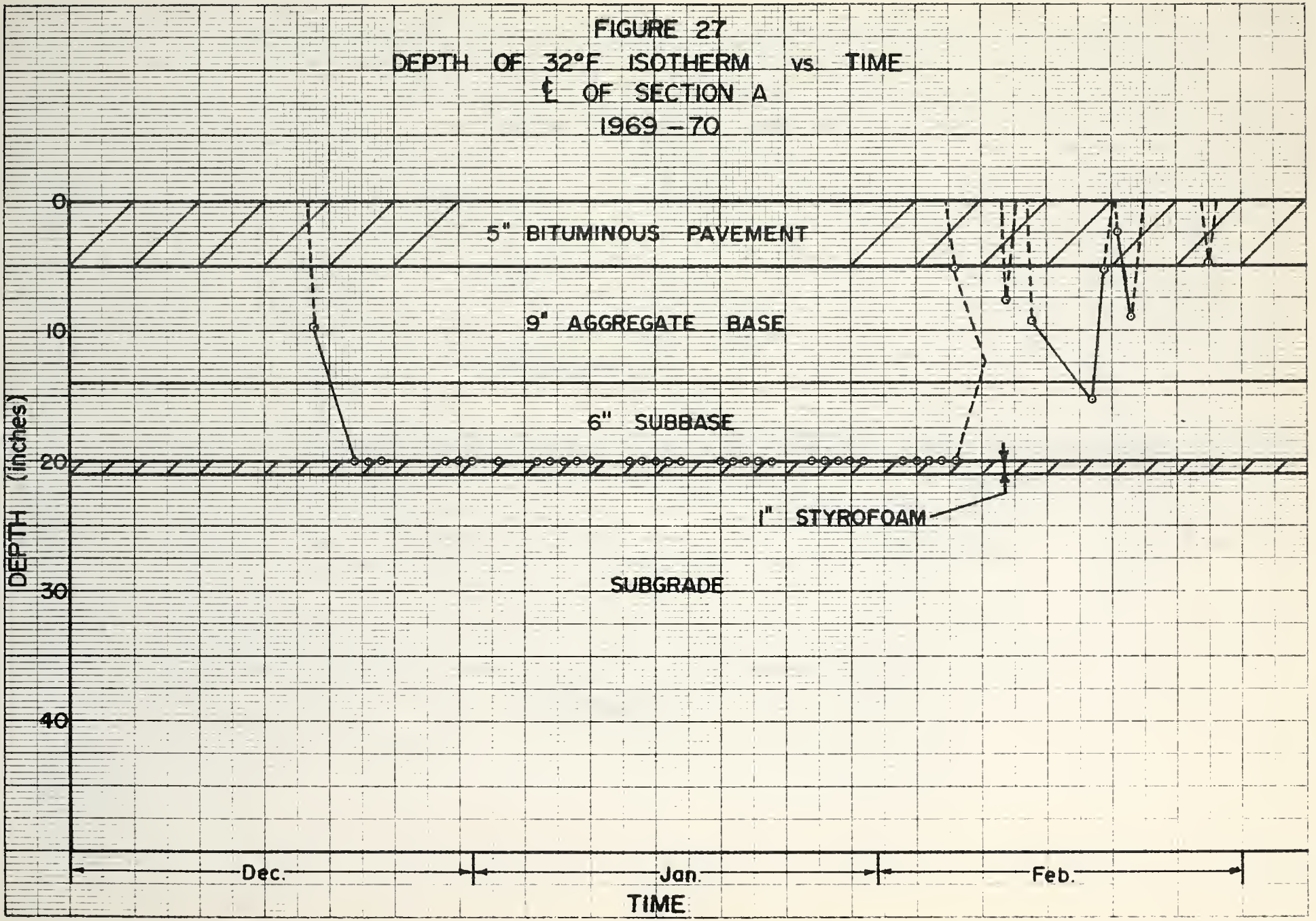
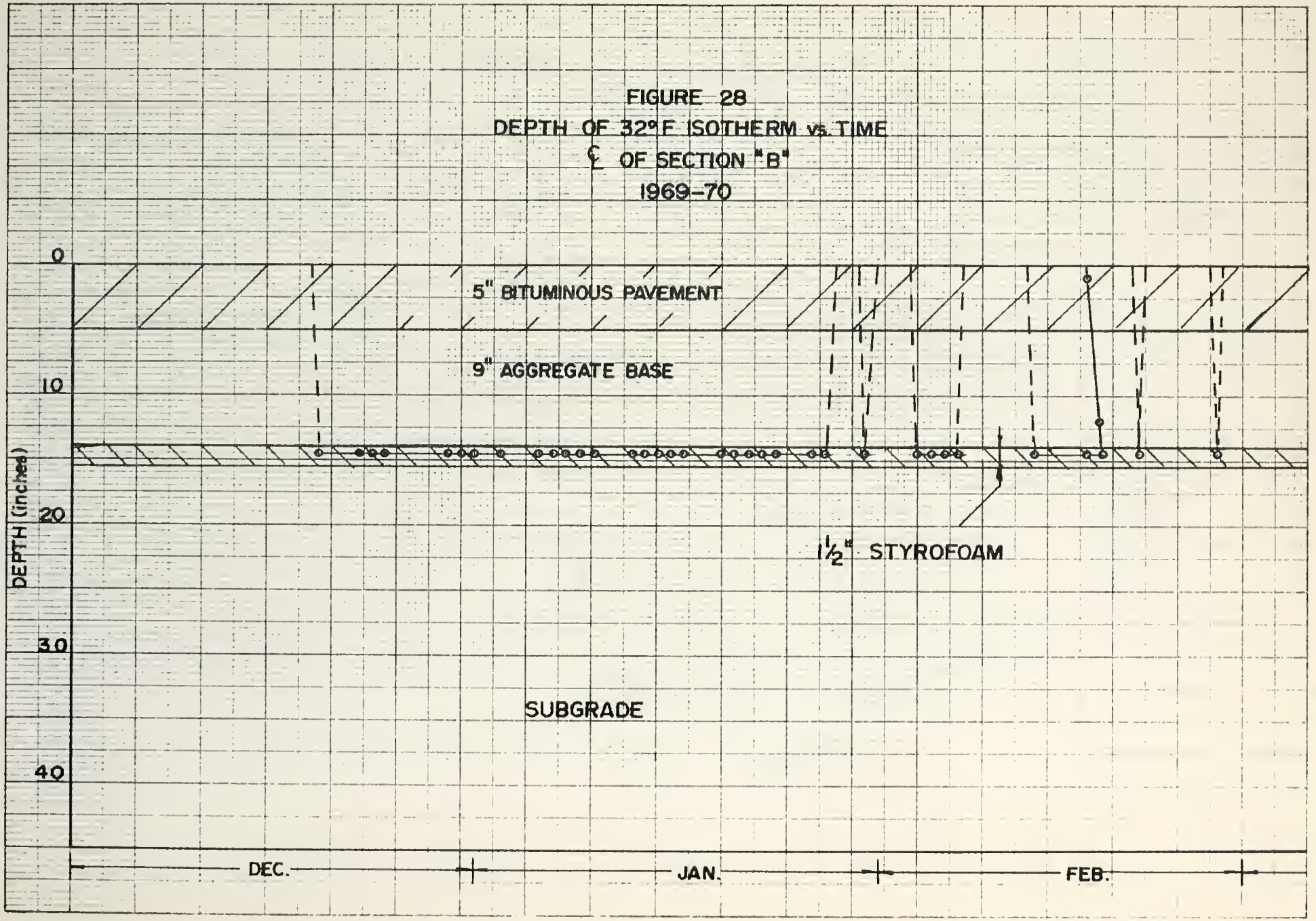


FIGURE 27
DEPTH OF 32°F ISOTHERM vs. TIME
℄ OF SECTION A
1969 – 70
0
10
20
30
40
DEPTH (inches)
5" BITUMINOUS PAVEMENT
9" AGGREGATE BASE
6" SUBBASE
1" STYROFOAM
SUBGRADE
Dec.
Jan.
Feb.
TIME

FIGURE 28
DEPTH OF 32°F ISOTHERM vs. TIME
℄ OF SECTION "B"
1969–70



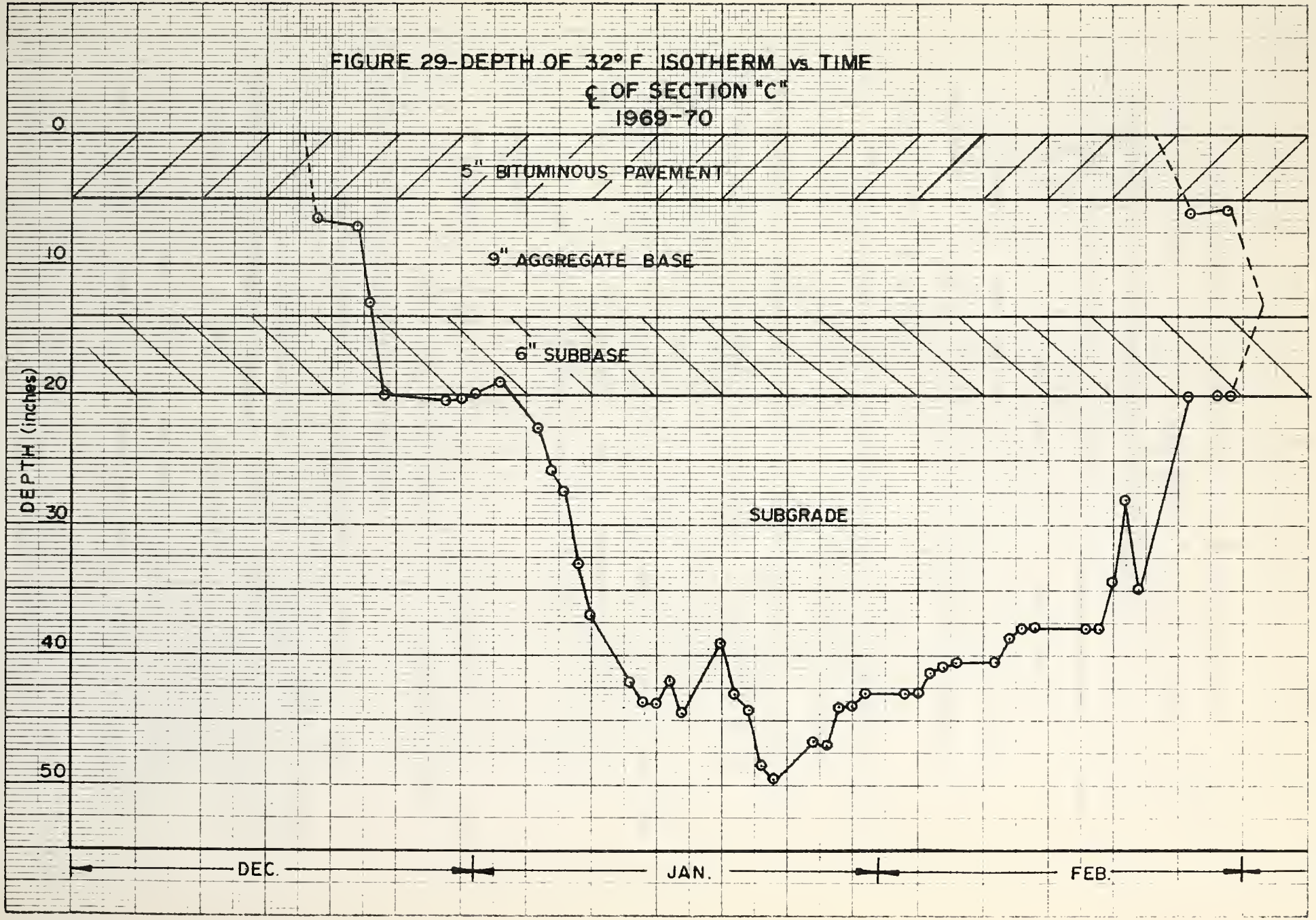


FIGURE 29-DEPTH OF 32° F ISOTHERM vs. TIME
℄ OF SECTION "C"
1969-70
0
10
20
30
40
50
DEPTH (inches)
5" BITUMINOUS PAVEMENT
9" AGGREGATE BASE
6" SUBBASE
SUBGRADE
DEC.
JAN.
FEB.

This fact is not illustrated in Figure 27. From a practical standpoint there was no significant frost penetration into the subgrade at the centerline of the insulated sections, whereas for the control section the depth of frost penetration into the subgrade was about 30 inches.

The materials above the insulation thaw sooner than the corresponding materials in the control section, though they may partially or completely refreeze above the insulation a number of times before final thawing.

The maximum depth of frost penetration in the control section was about 50 inches. The exact depth is not known since no data were obtained on the weekend of January 24 and 25 when maximum penetration may have occurred. The depth of penetration is relatively large considering that the freezing index was only 673 degree-days. In fact if one assumes maximum frost penetration on January 25, the cumulative degrees-days would be only 560. The difference (113 degree-days) was accumulated while the subgrade was in the process of thawing from the bottom up.

The subgrade in the control section thawed entirely from the bottom up. While this is desirable, it normally is not the case for a soil that exhibits detrimental frost heaving.

The deep frost penetration resulting from a relatively low freezing index, and the fact that the subgrade thawed entirely from the bottom up indicate low ice content in the frozen subgrade, i.e. little or no frost heave. This tends to substantiate the statement made earlier in the report that soil and moisture conditions in Section C (and in Section A too) are such that one would expect the section to

be relatively free from any detrimental frost heaving.

VISUAL APPEARANCE OF THE SECTIONS

Some transverse and longitudinal cracking of the bituminous surface has developed, but the cracking does not appear to be inconsistent with cracking that has occurred outside the limits of the test site. At station 101 (the location of Section B thermistors) there is a transverse crack that completely cuts the north lane and extends about 2 feet into the south lane. Starting at station 101 there are intermittent longitudinal cracks in the south lane, just off the centerline, and these cracks extend east for a distance of about 60 feet. Section C appears to be free of cracks except at the transition between C and A (sta. 104). At this point there is a transverse crack about 6 feet long in the middle of the south lane. Intermittent longitudinal cracks run east from sta. 104 for a distance of about 30 feet, again in the south lane just off the centerline.

The crack patterns that have developed in the test area are not inconsistent with crack patterns that have developed outside the limits of the test area, both to the east and to the west. Thus it is felt that, at the present time, it is impossible to attribute the cracking in the test area to the presence of the insulation, even though most of the cracking in the test area is over the insulated sections.

Comparison of future distress of cracked areas inside and outside the test site might be of considerable value in determining the effect

of the insulation on the structural performance of the pavement section.

SURFACE ICING

The potentially serious problem of differential icing of the road surfaces of insulated and uninsulated sections has created considerable concern in many highway departments. The New York State Highway Department recently suspended the use of foamed plastic insulation in highways pending the results of a two year study of the icing problem.

Just how serious the icing problem may be is open to question at the present time. In the author's opinion the problem could be very serious in cases where short insulated sections are installed on curves and/or hills on high speed highways. Straighter alignments, flatter grades, and reduced speeds should all tend to reduce the seriousness of the problem. Also the proper combination of weather conditions is a factor, and thus some geographic locations will be more prone to icing conditions than others.

Assuming that differential icing is a problem, it may be possible to alter design details, such as the thickness of the insulation and the depth at which the insulation is placed, so that the problem is minimized in future designs.

To adequately study the icing problem one should have continuous monitoring of all variables involved in icing whenever a potential icing situation arises. Direct observation by the investigator during icing periods would also be desirable.

An attempt was made to study the icing problem at the site to see if some indication of the potential severity of the problem could be obtained. The analysis is admittedly somewhat crude since the existing instrumentation at the site is simply not adequate to permit a detailed study of the problem. The analysis was made from the standpoint of road temperatures only. Daily temperatures 1 inch below the pavement surface were used in the analysis since pavement surface temperatures were not available. In addition Sections B and C were used in the analysis since the difference in pavement temperatures was generally the greatest in those two sections.

Figures 30 and 31 are temperature vs. time plots for thermistors on the centerline and 1 inch below the surfaces of Sections B and C. Figure 30 shows that during the general cooling period (Dec. and Jan.) the surface of the insulated section is generally colder than the surface of the control section. Thus Section B cools to 32°F sooner than Section C, and, when frozen, warms to 32°F later than Section C. Therefore, if other conditions are favorable, Section B will ice sooner than Section C, and the ice will remain on Section B longer as the sections warm up.

Scaling from the graph the number of days that the two sections were below 32°F through January 26 yields 31.8 days for Section B and 26.5 days for Section C. Thus, considering pavement temperatures only, the potential for icing on Section B is approximately 20 percent greater than on Section C. During the same time period there were 7 times when an icing situation could have developed. In addition the time lag between the freezing or thawing of the two

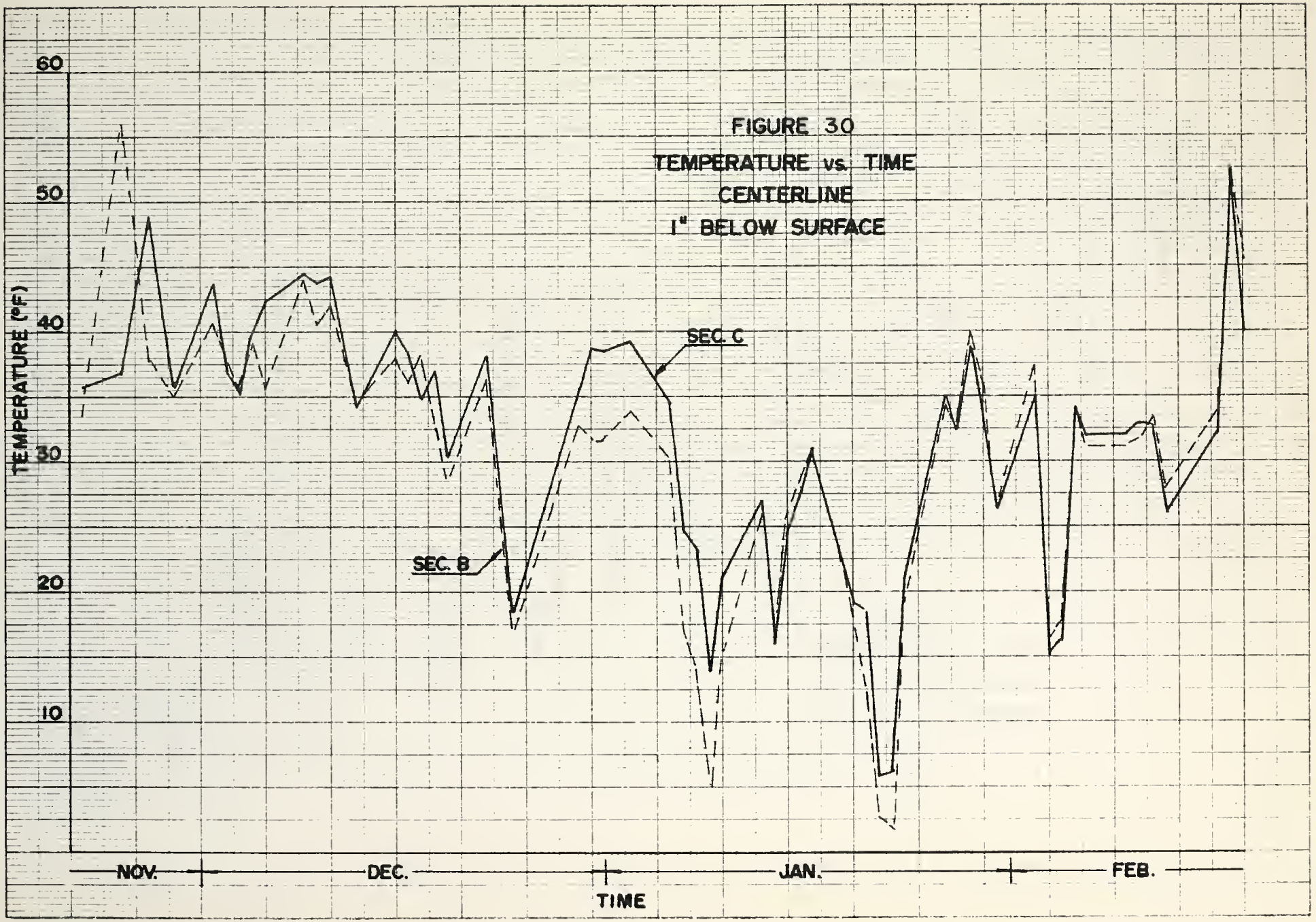


FIGURE 30
TEMPERATURE vs. TIME
CENTERLINE
1" BELOW SURFACE
SEC. C
SEC. B
TEMPERATURE (°F)
60
50
40
30
20
10
NOV.
DEC.
JAN.
FEB.
TIME

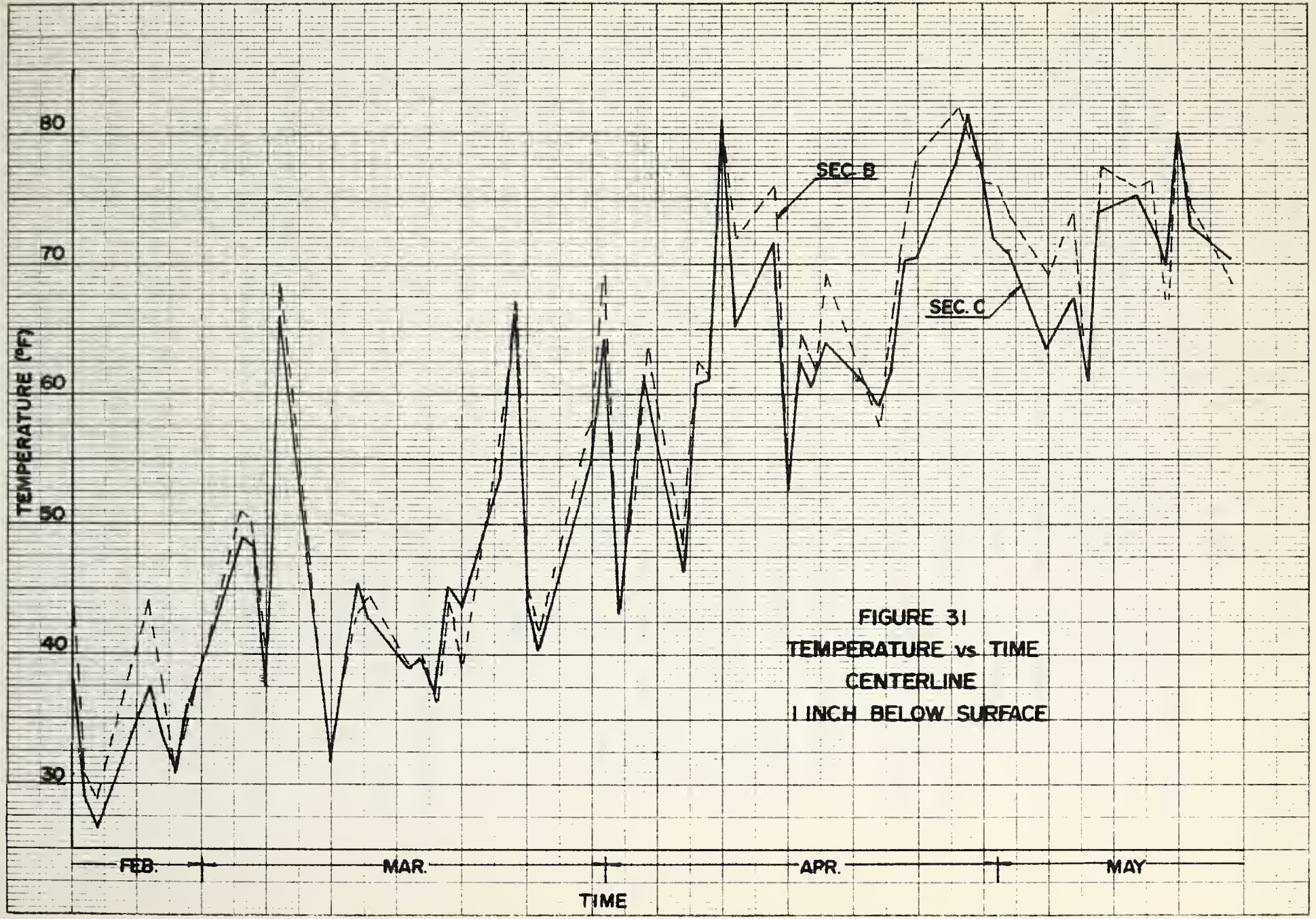


FIGURE 31
TEMPERATURE vs TIME
CENTERLINE
1 INCH BELOW SURFACE

sections may reach a maximum of about 18 hours.

Figures 30 and 31 also show that once the general warming trend begins, in this case about the end of January, the above situation may be reversed, i.e. the uninsulated section may become the critical one with regard to icing. Considering the period after January 26 Section B is below freezing 15.5 days and Section C is below freezing 17.8 days. Thus the icing potential during that period is about 15 percent greater for Section C than for Section B. Icing could have occurred during that period 14 times.

Figure 32 shows plots of cumulative freezing degree-days vs. time for the two sections. The plots were obtained from Figures 30 and 31 by determining the area between the curves and the 32°F line, for temperatures below 32°F only. Note that the degree-day curves diverge during the general cooling period, until about the end of January, and then converge over the remainder of the season when there is a general warming trend in the temperatures. The divergence of the curves simply means that the surface of the insulated section is, in general, colder than the surface of the control section, whereas for convergence the opposite is true. By January 26 the insulated section had accumulated 28 percent more freezing degree-days than the control section. At the end of the season the difference had been reduced to about 14 percent.

Although one hesitates to draw conclusions from an analysis as crude as this, it does appear that differential icing can be expected to occur when a highway contains insulated sections. In addition, and perhaps more important, the general temperature trend at the time an

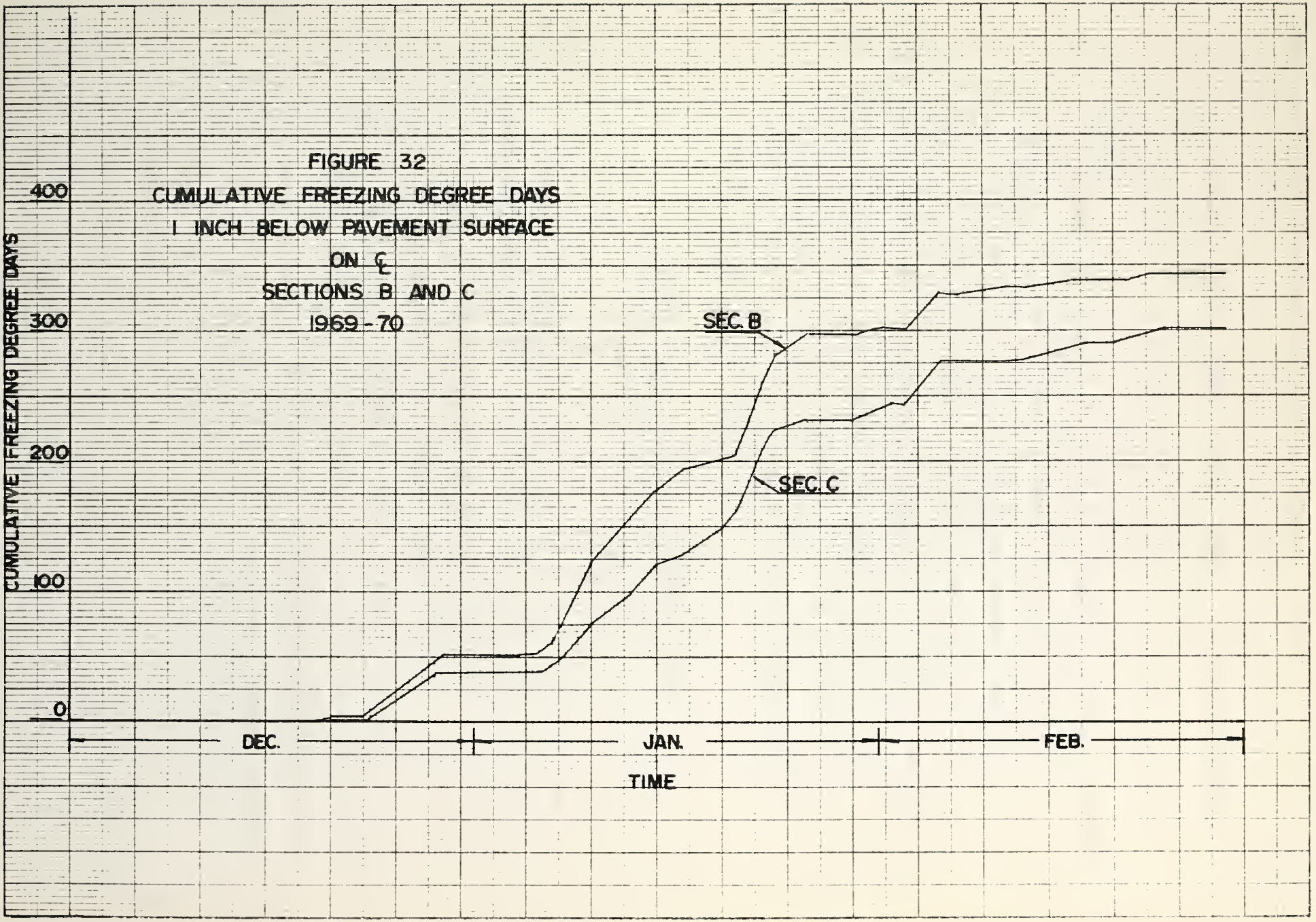


FIGURE 32
CUMULATIVE FREEZING DEGREE DAYS
1 INCH BELOW PAVEMENT SURFACE
ON ℄
SECTIONS B AND C
1969-70
CUMULATIVE FREEZING DEGREE DAYS
400
300
200
100
0
SEC. B
SEC. C
DEC.
JAN.
FEB.
TIME

icing situation arises appears (in most cases) to determine whether the insulated or the uninsulated portions of the highway will be critical.

One additional comment should be made regarding pavement temperature differences. The above analysis of the freezing and thawing periods raises the question of possible significant pavement temperature differences during the summer months; i.e. does the pavement surface over insulated sections get significantly warmer than that over uninsulated sections? Unfortunately this possibility could not be investigated for the present installation due to the fact that the temperature range of the thermistors is not great enough to obtain reliable temperatures above about 80°F.

PART II - GROUND TEMPERATURE PREDICTIONS

TEMPERATURE PREDICTION METHOD

Computer programs have been developed at Purdue to solve the problem of conduction heat flow through soil-water systems, Ho [1]. The programs are for one-dimensional and two-dimensional heat flow, and were developed using the method of finite difference. The programs are general in nature and can be used for any soil-water system where either one or two-dimensional heat flow conditions exist. The use of the programs at Purdue has been confined primarily to the frost penetration problem in highways. Perhaps the greatest advantage of them is the fact that they allow relatively rapid comparison of alternate thermal designs.

INPUT DATA REQUIRED

The computer programs were developed with the idea of using them as design tools and, therefore, the required input information was limited to data that are either readily available in the literature or that are easily obtained in the field for a relatively low cost.

The input information required consists of a cross section showing material boundaries, properties of the various materials (unit weight, water content, volumetric heat capacity, thermal conductivity, and ice formation equations), initial boundary temperatures in the soil, surface transfer coefficient(s), and daily mean air temperature. Other input data, such as the initial temperature distribution in the section, is required, but is obtained from the above data.

Once the cross section, including material boundaries, is known, a solution mesh can then be drawn for the section. One such mesh used for temperature predictions in Section A is shown in Figure 33. The lateral thermal boundaries were established in this section by assuming vertical heat flow at the highway centerline and at the ditch bottom. The upper boundary is of course fixed by the pavement and ground surfaces, and the lower boundary is a horizontal line at any appropriate depth. The mesh is then drawn using horizontal and vertical lines, both of which must be continuous through the section. The result is a mesh consisting of many rectangular cells.

Governing criteria for drawing the mesh are: a) cell boundaries should coincide, as nearly as practical, with material and section boundaries; b) if interpolation is to be avoided, any point at which a temperature prediction is desired must coincide with the center of a

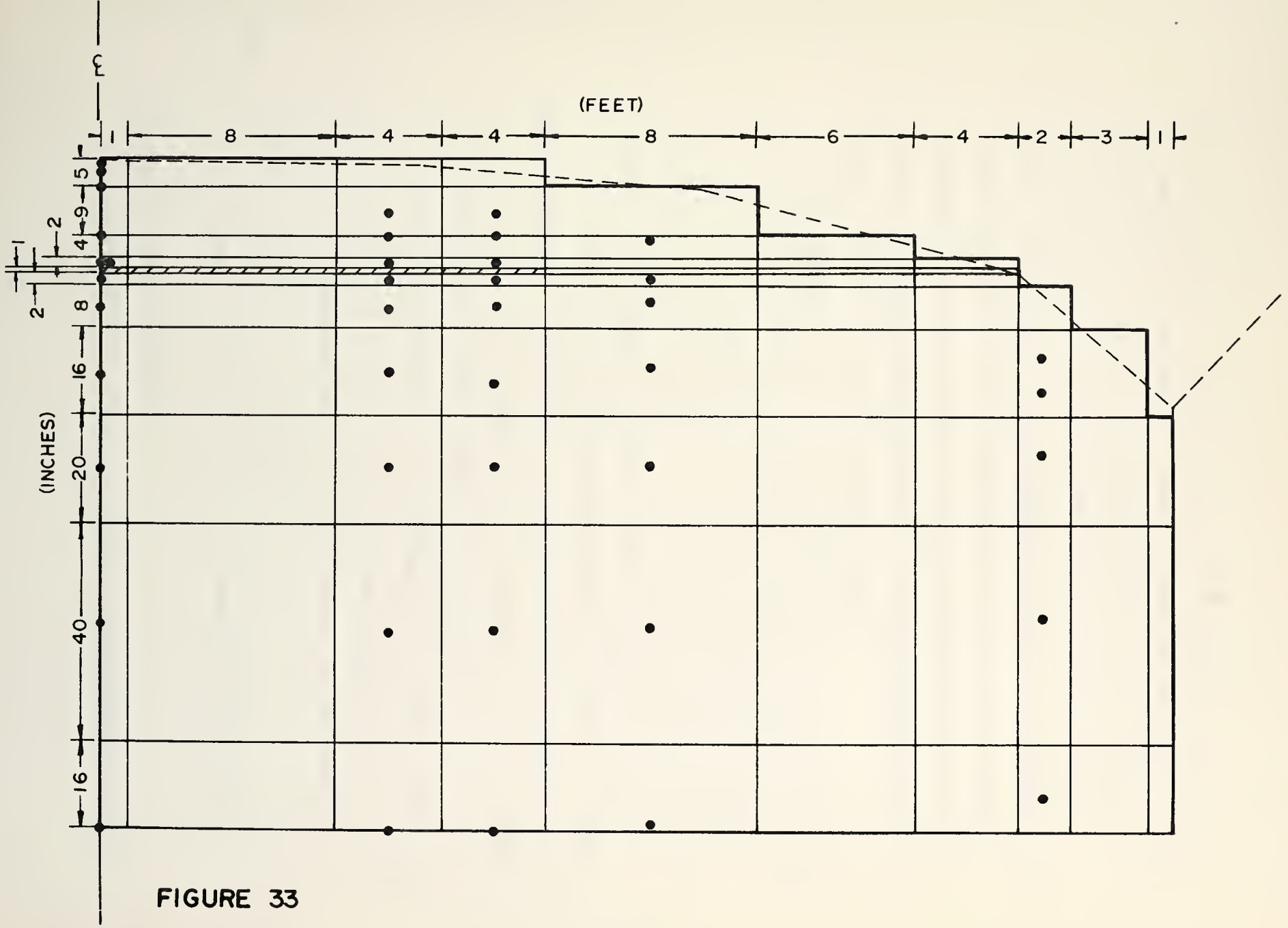


FIGURE 33

SECTION A MESH

cell, since that is the point at which the temperature is predicted; c) computer time, and therefore cost, increases as the number of cells increases, thus closely following material and section boundaries by the use of many cells which have small vertical and/or horizontal dimensions will result in high computer costs; and d) the maximum time increment that can be used in solving the finite difference equation is governed by the size of the cells, with thin and/or narrow cells requiring a smaller time increment and thus more computer time to obtain a solution for a given freezing season.

Once the mesh is drawn, the following input data can be obtained: the horizontal and vertical dimensions of each cell, the properties of the material in each cell, the ice formation equations for each cell, the initial temperature at the center of each cell, the initial lower boundary temperatures, the surface transfer coefficient for each vertical column of cells, and the cell type for each cell. The cell type informs the computer about the thermal boundary conditions on the four sides of each cell. Figure 27 is Toenniessen's report [5] shows the various types of cells needed for the 2-D mesh.

The one-dimensional case is much simpler and requires significantly less computer time because there is only one column of cells. However, the predicted temperatures that are obtained are for one lateral position only, viz., the highway centerline.

POTENTIAL SOURCES OF ERROR IN THE TEMPERATURE PREDICTIONS

Upper Boundary Temperature

The upper boundary temperature used for temperature predictions

was the mean daily air temperature, i.e. the average of the maximum and minimum temperatures for each day. It is possible that better agreement between predicted and measured temperatures could be obtained by using the average of the mean hourly temperatures for each day, since the difference between the mean daily temperature and the average of the mean hourly temperatures for a given day may be $3^{\circ}F$ or more depending on the shape of the temperature-time curve for that particular day. No comparison of these two approaches was made; however, it is thought that agreement between predicted and measured temperatures in the upper portion of a section would improve for some days if the average of the mean hourly temperatures for each day was used. On the other hand if one is simply looking for the minimum temperature at a given point for a given freezing season, using the mean daily temperature should give satisfactory results since, over the season, the mean daily temperature is likely to contain both positive and negative errors which will tend to cancel out.

Precision in the Locations of the Upper Boundary and Material Boundaries

The positions of the upper boundary and the material boundaries should introduce little error into the temperature predictions if these boundaries are determined with normal engineering precision. Obviously as the variation in material properties increases, the position of the material boundaries becomes more important. On the other hand, the boundaries in any given section generally have some slope, and since restrictions in drawing the solution mesh prevent exact matching of cell boundaries with sloping boundaries, determining

the boundary positions with normal engineering precision is sufficient. Also it should be noted that in a design application the upper boundary used would be the design cross section, which is likely to differ somewhat from the as-built cross section, especially in the slope area. Thus how well the as-built cross section corresponds to the design cross section is much more important than extreme accuracy in the design cross section.

Locations of the Lateral Boundaries

The lateral boundaries are located at points where the heat flow is vertical, or approximately vertical. Generally the highway cross section will be sufficiently symmetrical about the centerline to permit the assumption of vertical heat flow at that point. Note that if this assumption is made, computer time will be significantly reduced since a solution need be obtained for only one-half of the highway section. It is possible that situations may arise for which the assumption of symmetry about the highway centerline is not valid. Sections in which the soils differ considerably in the lateral direction, and sections in which the design cross section is not symmetrical, would be two such situations. There are two possible methods of obtaining a solution for such situations. The first method would be to assume symmetry about the centerline and obtain a solution for the more critical half of the highway. The second method would be to obtain a solution for the complete cross section. The second method should not be used unless the additional cost of the solution can be justified by the increased accuracy of the results.

In the 1-D program the lateral boundaries are fixed by the width (nominally 12 inches) selected for the single column of cells. Normally the single column of cells is positioned so that the centerline of the cells coincides with the centerline of the highway. The isotherms shown in Figures 18 through 23 indicate the area(s) in each of the three sections where the 1-D analysis could be applied.

In the 2-D case the centerline is generally used as one lateral boundary and the other lateral boundary is placed at the ditch bottom in cut sections or in the area of the toe of the slope in fill sections. Since isotherms tend to be parallel to the ground surface, they must be approximately horizontal at those two locations (assuming that the ground surface is either horizontal or rises beyond the toe of the slope in fill sections). This does not mean that the heat flow is exactly vertical in those areas, since the points at which the isotherms are horizontal are not likely to lie on a vertical line. Nevertheless, assuming vertical heat flow at these points should be a reasonable assumption and should not significantly affect the predicted temperatures at points of interest beneath the insulation, since the distance from the insulation to the assumed lateral boundary is large.

Matching Section and Material Boundaries with Cell Boundaries

The fact that the finite difference solution mesh is divided into cells by horizontal and vertical lines, both of which must be continuous through the mesh, makes it impossible to exactly match cell boundaries with sloping boundaries in the section. As the slope of the boundaries increases, the matching becomes more approximate.

Although close matching can be accomplished by the use of much smaller cells, the number of cells is likely to become so large that the cost of obtaining a solution becomes prohibitive. Close matching of the boundaries is important where material properties differ markedly, primarily between the subgrade and pavement surfaces, with insulation boundaries being the most critical. As the variation in material properties decreases, close matching of the boundaries becomes less important. Ground surfaces beyond the shoulder point generally must be roughly approximated because of cost, but in the slope area snow cover is likely to be much more important than close matching of the slope surface. For most highway sections a trade-off will be necessary between the possible increase in accuracy of the solution if boundaries are closely matched, and the increase in the cost of obtaining such a solution. It should be noted that, with regard to the matching of boundaries, a finite element solution would offer much more flexibility than is present in the finite difference solution.

Material Properties

The properties of the insulating material should be furnished by the manufacturer, and should be sufficiently precise to cause no significant error in the temperature predictions. However the properties of the other materials in a highway section are less accurately known. The soil properties, e.g., dry unit weight and water content, determined from soil borings may be subject to considerable error, and using them to obtain additional properties such as thermal conductivity and specific heat from the literature may introduce additional error.

Also it must be remembered that thermal conductivity and specific heat values given in the literature may not be very accurate. It is likely that both positive and negative errors will be introduced, and in the end result will tend to at least partially cancel out.

The alternative to using properties obtained from the literature is to actually measure those properties. At the present time it is felt that the cost of measuring the properties could not be justified by the possible increased accuracy of the results, especially since the problems involved in measuring the properties are very likely to result in measured values that are no more accurate than values obtained from the literature. Also, temperature predictions obtained in this study indicate that the greatest improvement will result from the reduction of errors due to sources other than material properties.

At the present time it is the author's opinion that the only realistic approach to follow in an actual design situation is to determine the dry unit weights and water contents of the soils with considerable care, and then use those properties to obtain the other required soil properties from the literature. This is the approach that was followed in this study, and the results are considered satisfactory for design purposes.

Moisture Transfer

One of the assumptions made by Mr. Ho in the development of both the 1-D and 2-D solution was that moisture transfer was negligible. The freezing of a frost-susceptible soil that has access to water is likely to result in considerable moisture transfer, and even if the

soil doesn't freeze the moisture content in the upper portion of the subgrade will tend to increase during cold weather due to the fact that moisture will move from warm to cold along a temperature gradient. The transfer of moisture will result in changes in both the thermal conductivity and the volumetric heat capacity of the soil. If, during freezing, enough moisture is transferred to produce heaving, the dry unit weight will decrease and a further change in the thermal conductivity will occur. Also with moisture transfer during freezing the latent heat removed during the phase change from water to ice is removed at a higher elevation in the soil and this tends to retard the penetration of freezing temperatures.

Since moisture transfer is likely to occur, the assumption of no moisture transfer appears at first glance to be poor one. However, in the design of insulated highways the zone of interest is the subgrade beneath the insulation, and with proper design there should be little or no freezing in that zone. Thus the assumption of no moisture transfer is a reasonable one for the zone of interest. The assumption should also be reasonably valid for non-frost-susceptible (non-heaving) soils, since, even with freezing, the amount of moisture transfer in a coarse-grained (non-heaving) soil is relatively small. The error introduced by the assumption will tend to increase as one goes from unfrozen to frozen soils and as the soils go from non-frost-susceptible to highly-frost-susceptible. However, if this assumption had not been made, it would be necessary to monitor moisture changes in the soil. Such a requirement would not be very practical for design applications. It is thought that the best approach for design purposes

would be to determine the moisture content of the soil late in the Fall, prior to initial freezing, and accept them as being constant throughout the freezing season.

Initial Temperature Distribution in the Section

Estimating the initial temperature distribution in the section is very likely to introduce considerable error in the predicted temperatures at the beginning of the prediction period. The solution, based on the use of incorrect initial values, will tend to converge to the correct solution over some period of time, Ho [1]. The time period required for convergence depends on the magnitude of the error in the initial values. For a design situation where the initial temperature distribution is estimated, it is recommended that temperature predictions be started at least one month in advance of the time at which temperature predictions are desired, to allow ample time for the convergence to take place. This approach was considered to be unnecessary for the test sections since measured ground temperature data was available. However, it now appears that even for the test sections the initial error that is present for some thermistor locations might have been reduced had temperature predictions been started 10 to 15 days in advance of the date on which initial temperature comparisons were made.

Surface Transfer Coefficient

To date, temperature predictions for the three sections have been obtained using a surface transfer coefficient of 1.0, except

that for Section B a 40 day period was run three different times using values of 1.0, 0.9 and 0.8 to obtain some information on the sensitivity of the predictions to the surface transfer coefficient. The results for values of 1.0 and 0.8 are shown in Figure 34. A curve for the 0.9 value would lie between the two curves shown. The curves are for a point on the centerline and at 1 inch below the insulation. The maximum difference between the curves is about $1^{\circ}F$. Also it was found that the effect of the surface transfer coefficient on the predicted temperature decreased with depth.

The question of what surface transfer coefficient to use is a difficult one because of the number of variables involved. The coefficient will vary with the type of surface and exposure conditions. In addition, exposure conditions are likely to vary somewhat from year to year. To obtain correct coefficients for a given season it would be necessary to have continuous surface temperature readings for each type of surface and exposure condition. Obtaining such measurements for design purposes would not be practical. Until further work is done on this problem, it is recommended that a coefficient of 1.0 be used for temperature predictions, with the recognition that the predicted temperatures will be lower than the actual temperatures. It is anticipated that the difference will be small, but that it will increase as the severity of the winter increases.

Prediction of Lower Boundary Temperatures

There are currently four options in the computer programs for handling the lower boundary temperatures. One option is to assume no

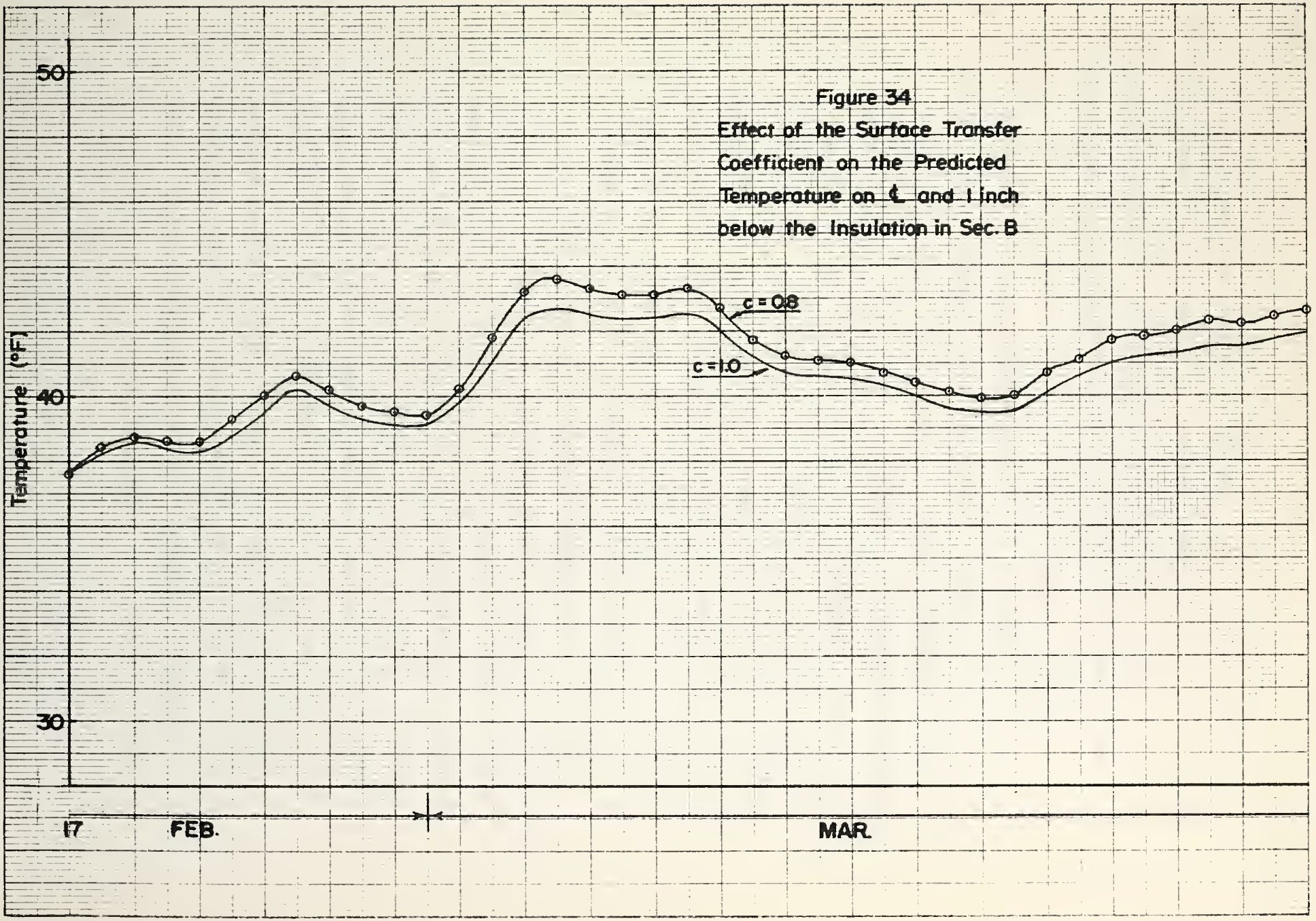


Figure 34
Effect of the Surface Transfer Coefficient on the Predicted Temperature on ℄ and 1 inch below the Insulation in Sec. B

heat transfer across the lower boundary. This is not a realistic assumption for the case of an insulated highway, since the normal geothermal flow of heat results in a substantial quantity of heat being transferred across the lower boundary. The second option is to assume a constant temperature at the lower boundary. However, examination of figures presented earlier in the report indicates that this is not a realistic assumption either. Figure 12 shows the variation of temperature with time at a depth of about 10 feet on the centerline of each of the three sections. The difference between the temperature on November 18 and the minimum measured temperature is approximately $14^{\circ}F$ for Sections A and C and $12^{\circ}F$ for Section B. Also, Figures 15, 16 and 17 show the lateral variation in temperature from the centerline to the outermost string of thermistors for the deepest thermistors in each of the three sections. These figures show maximum lateral variations of about $11^{\circ}F$ for Section A, $10^{\circ}F$ for Section B, and $3^{\circ}F$ for Section C. The actual lateral variation will be greater, especially so in Section C, since the solution mesh extends beyond the outermost string of thermistors in each section. Thus considering both time and lateral position, the total variation in the boundary temperatures over the freezing season may be as much as $30^{\circ}F$ (even more for a more severe freezing season). Thus assuming a constant temperature at the lower boundary will introduce significant error. Possible exceptions would be cases where the depth to the lower boundary is great or where the lower boundary is below the water table. The third option is to use the predicted temperatures at the centers of the cells in the bottom layer of the solution mesh as the

lower boundary temperatures for the next calculation. This option, or some modification of it, appears to be the most practical one for design applications, since the fourth option requires inputing actual measured temperatures at the lower boundary.

Initially the solution meshes for the sections were drawn such that the bottom layer in each mesh was about 40 inches thick. Agreement between predicted and measured temperatures in the lower layers of these meshes was not good. The use of the predicted temperatures at the centers of the bottom layer of cells as the lower boundary temperatures for the next calculation assumes that the temperature gradients between those points are zero, when in fact, the actual temperature gradients between those points increase with depth (during the freezing season). Thus the transfer of the temperatures of the bottom cells to the lower boundary introduces considerable error in the lower boundary temperatures, and the error tends to accumulate with successive calculations. To further complicate the problem, the number of times the temperatures are transferred depends on the time increment required to maintain a stable solution, and that time increment is generally one-half hour or less. The end result is that the temperature may be transferred fifty to one hundred times for each twenty-four hour period. In order to reduce the error resulting from the transfer of temperatures, a two-inch thick layer was placed at the bottom of each solution mesh to reduce the distance over which the temperatures must be transferred. This significantly reduced the error, but the cumulative error over a period of about two months is still fairly large, as the results presented later in the report will show.

Other possible methods of predicting the lower boundary temperatures are being examined by Mr. Horton, and it is expected that a better method will be found by the time the final report on this project is submitted.

Snow Cover

Uncompacted snow is a good insulator, and the accumulation of a relatively shallow depth of snow cover on a highway section will significantly affect the rate of heat removal from the ground. Thus if snow cover is present, higher temperatures will tend to be maintained throughout the highway section.

Normally, snow cover is considered to be a factor only for locations outside the shoulder points. The contention is that snow removal operations keep the pavement and shoulder free of snow cover. This however is not strictly true, as snow will tend to accumulate on the pavement and shoulder surfaces for relatively short periods of time, with the amount of accumulation being a function of such factors as rate of snowfall, exposure of the pavement to any wind that is present, traffic density, type of snow removal equipment used, and the time interval between successive passages of snow removal equipment. Of special concern here is snowfall in the early morning hours from about midnight to 6 AM when traffic density may be very low, and when the passage of snow removal equipment is likely to be much less frequent. If intermittent, light snow cover is present on the pavement and shoulder surfaces, slightly higher temperatures will be maintained in the highway section. However, the error introduced into the solution

as a result of not considering snow cover between the shoulder points will be very small when compared to the error caused by not considering snow cover outside the shoulder points. Considering the difficulties involved in evaluating the depth and insulating effect of snow cover between the shoulder points, and the difficulty of including intermittent, light snow cover in the computer program, it appears that the only realistic approach to use in a design situation is to neglect snow cover between the shoulder points and accept the small error that will result.

Snowfall outside the shoulder points is allowed to accumulate, and, thus, snow cover on the slope surfaces is much more important than snow cover on the pavement and shoulder surfaces. Snow cover on the slopes will maintain significantly higher ground temperatures in the slope area, which in turn will tend to maintain higher ground temperatures throughout the highway section. Data presented later in the report show that neglecting to include the slope snow cover in the computer solution may result in significant errors in the predicted temperatures. Snow cover has not been included in any of the temperature predictions to date. Nevertheless, it is felt that the error in the predicted temperatures could be significantly reduced if a satisfactory method of including the slope snow cover in the computer program can be found. It is expected that if a satisfactory method is found, it will, of necessity, be somewhat approximate. Mr. Horton is currently planning to examine possible methods of including the slope snow cover in the computer program in hopes of finding a realistic method which can be used in design applications.

Considering the potential sources of error, it is presently thought that significant improvement in the temperature predictions can be obtained if a major portion of error resulting from snow cover on the slopes and from incorrect predictions of the lower boundary temperatures can be eliminated. Removing the error from any one of the remaining sources may or may not improve the temperature predictions, since the error removed may be a necessary compensating one.

COMPARISON OF 1-D AND 2-D TEMPERATURE PREDICTIONS

Initially, both 1-D temperature predictions on the centerline and 2-D temperature predictions were obtained for Section A. The predicted temperatures on the centerline were then compared to assess the agreement between the two solutions. Figure 35 shows the comparison for a point on the centerline and one inch below the insulation. Accumulating the absolute value of the daily difference between the curves for the time period shown and dividing by the total number of days gives an average daily difference of $0.5^{\circ}F$. Note that the difference from a given curve may be either positive or negative, as the 2-D curve tends to smooth out the hills and valleys in the 1-D curve. The maximum difference between the curves is $1.6^{\circ}F$ on January 30.

After examining plots such as the one shown in Figure 35, and considering the agreement between the 1-D and 2-D predictions obtained by Ho [1], it was decided that the agreement between the 1-D and 2-D predictions was sufficient to justify eliminating the 1-D predictions and concentrating only on the 2-D predictions. This decision was also

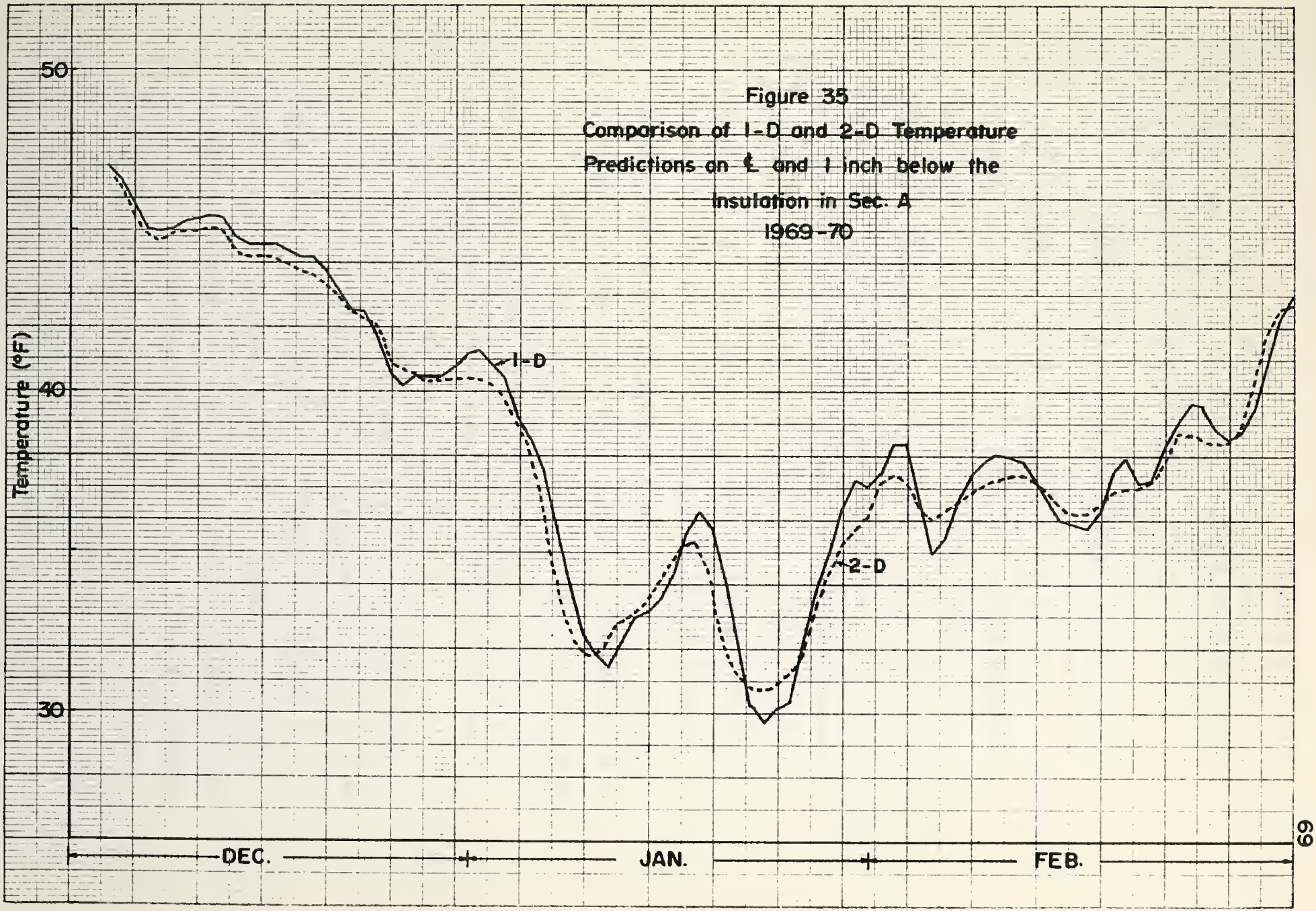


Figure 35
Comparison of 1-D and 2-D Temperature Predictions on ℄ and 1 inch below the Insulation in Sec. A
1969-70

influenced by the fact that a better comparison of alternate designs can be obtained with the 2-D solution.

COMPARISON OF PREDICTED AND MEASURED TEMPERATURES

Figures 36 through 41 show comparisons of predicted and measured temperatures at various depths and lateral positions beneath the insulation in Section A. The predicted temperatures shown in these figures were obtained by using the predicted temperatures at the center of a 2 inch thick bottom layer as the lower boundary temperatures for successive calculations. The curves for measured temperatures for 18 inches, 3 feet and 5 feet 6 inches below the insulation and 11 feet off the centerline show a sudden increase in temperature on February 3, with continued high temperatures through February. These high temperatures are attributed to instrument error. In addition, horizontal and vertical temperature gradients through the point 18 inches below the insulation and 11 feet off centerline indicate that the thermistor at that location was reading about $2^{\circ}F$ low for the period from December 4 to February 2. No correction was made for this error when the curve was plotted.

The minimum measured temperature at the top of the subgrade on the centerline of this section was obtained on January 23; thus the agreement between predicted and measured temperatures is, in the author's opinion, quite good through the freezing season. For the period from December 3 to January 23 the maximum difference between the predicted and the measured temperatures is about $4^{\circ}F$, however, for the majority of the comparisons the maximum error is in the range

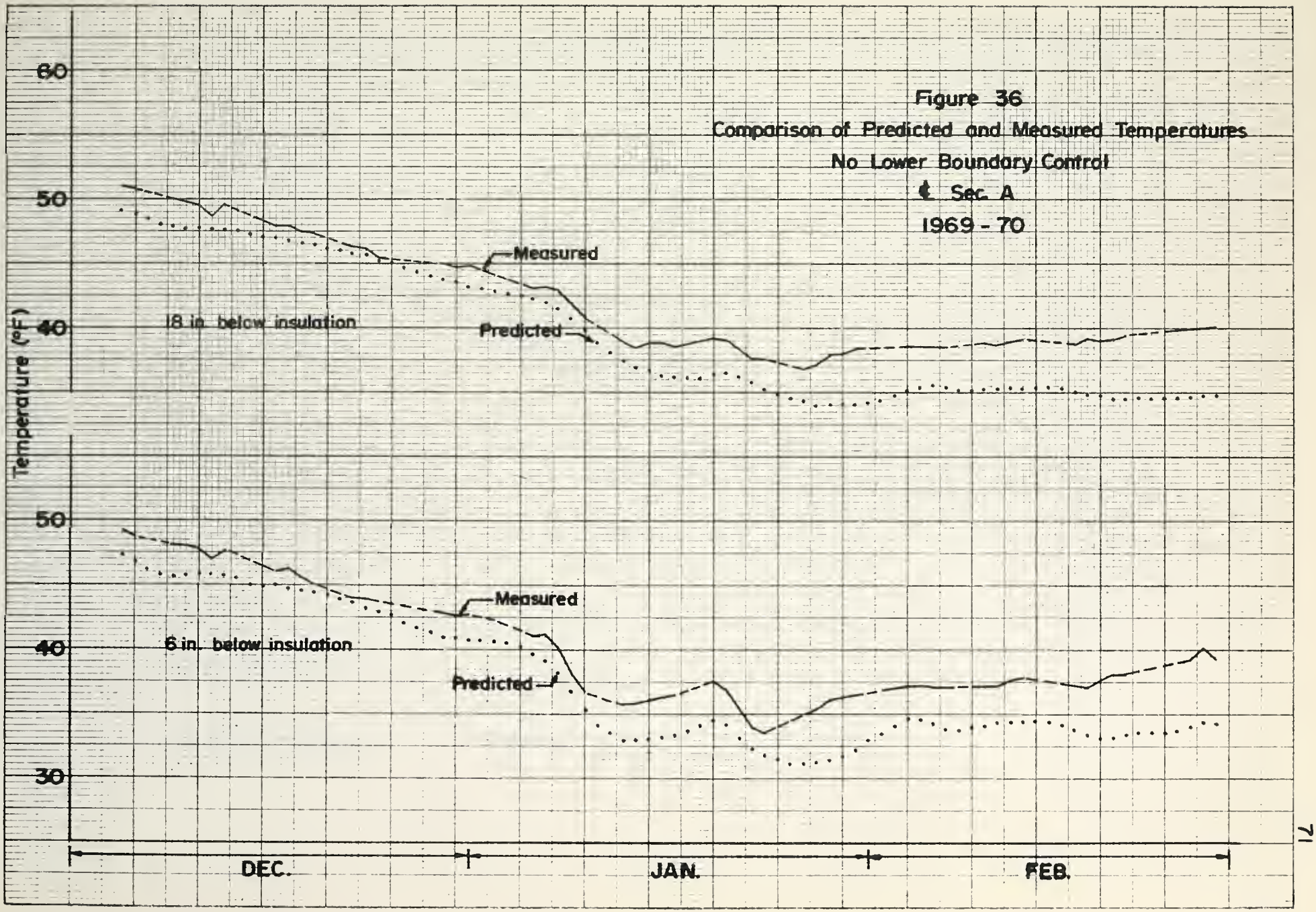


Figure 36
Comparison of Predicted and Measured Temperatures
No Lower Boundary Control
℄ Sec. A
1969 - 70
Temperature (°F)
60
50
40
50
40
30
Measured
Predicted
18 in. below insulation
Measured
Predicted
6 in. below insulation
DEC.
JAN.
FEB.

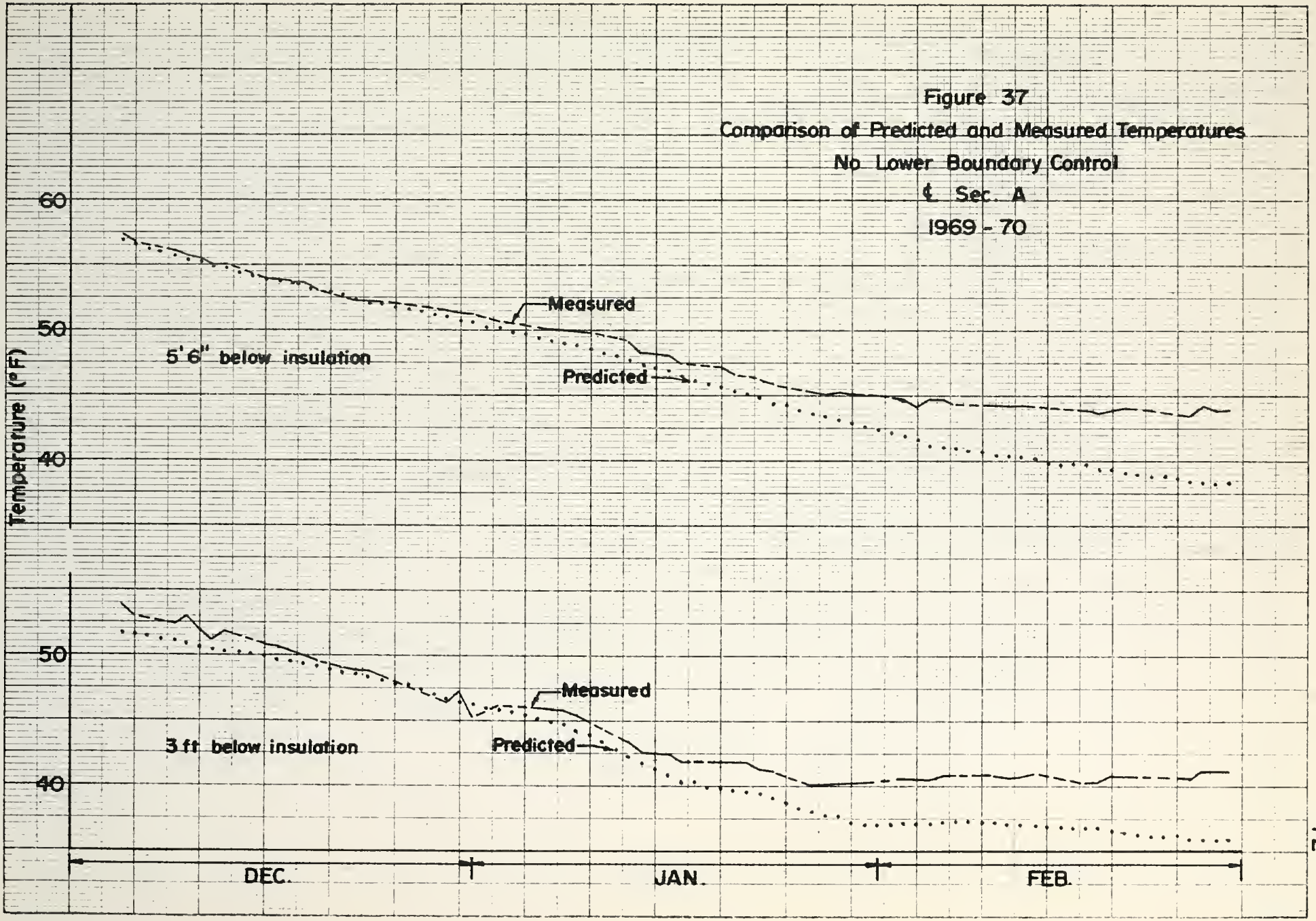


Figure 37
Comparison of Predicted and Measured Temperatures
No Lower Boundary Control
℄ Sec. A
1969 - 70
Temperature (°F)
60
50
40
5'6" below insulation
Measured
Predicted
50
40
3 ft below insulation
Measured
Predicted
DEC.
JAN.
FEB.

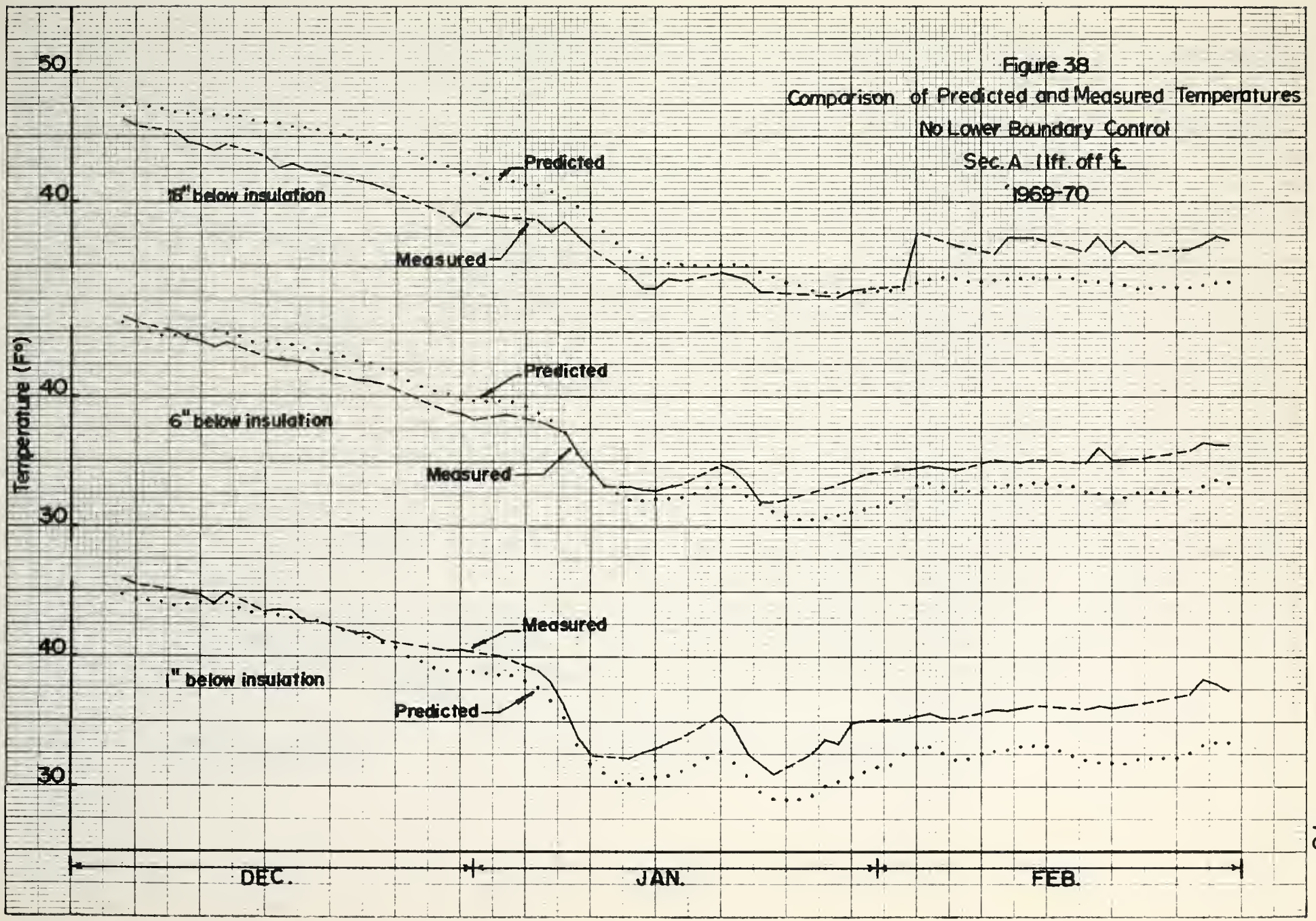


Figure 38
Comparison of Predicted and Measured Temperatures
No Lower Boundary Control
Sec. A Lift. off ℄
1969-70
Temperature (F°)
50
40
30
40
30
40
30
8" below insulation
Predicted
Measured
6" below insulation
Predicted
Measured
1" below insulation
Measured
Predicted
DEC.
JAN.
FEB.

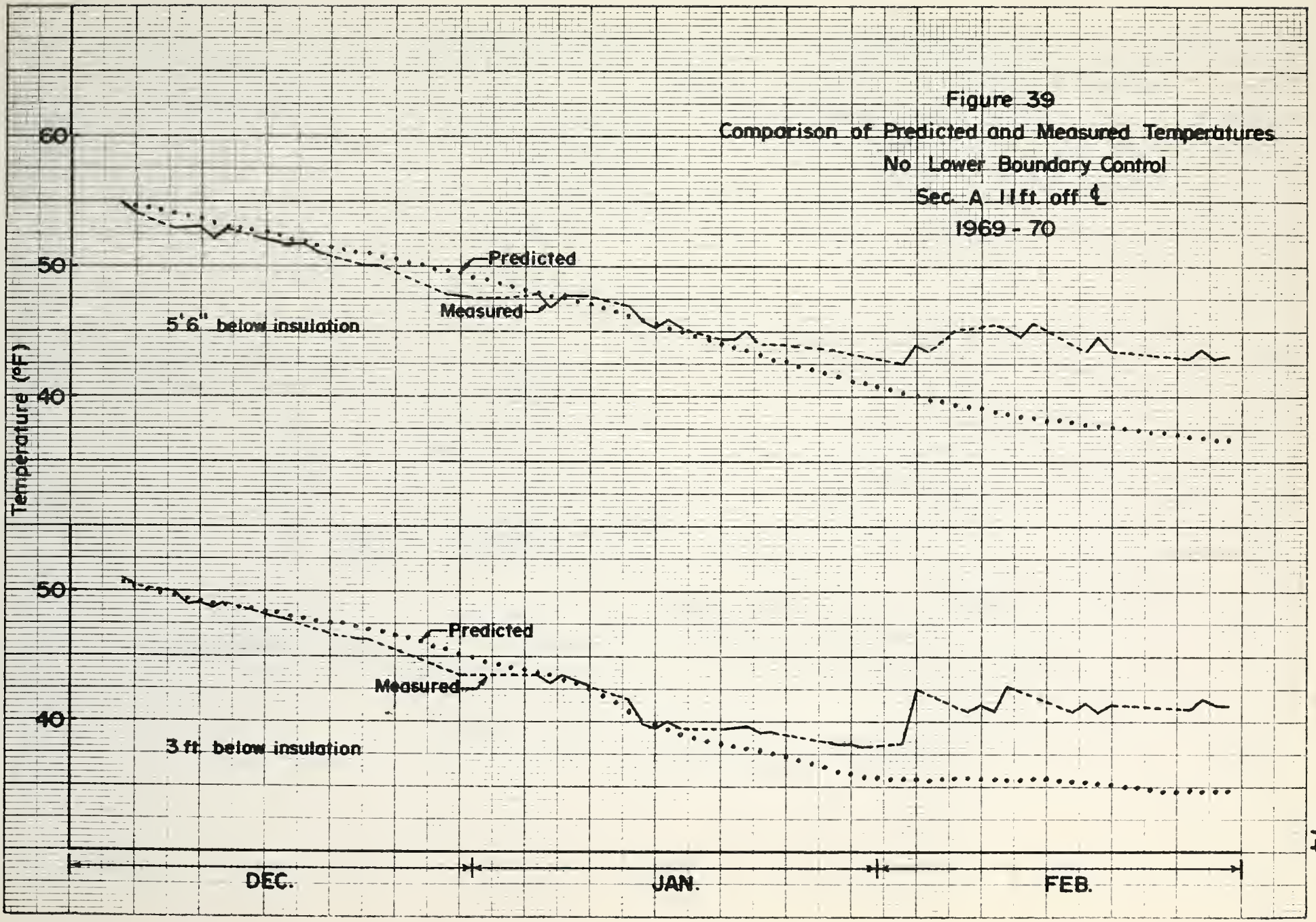


Figure 39
Comparison of Predicted and Measured Temperatures
No Lower Boundary Control
Sec. A 11ft. off ℄
1969 - 70
Temperature (°F)
60
50
40
Predicted
Measured
5'6" below insulation
50
40
Predicted
Measured
3 ft. below insulation
DEC.
JAN.
FEB.

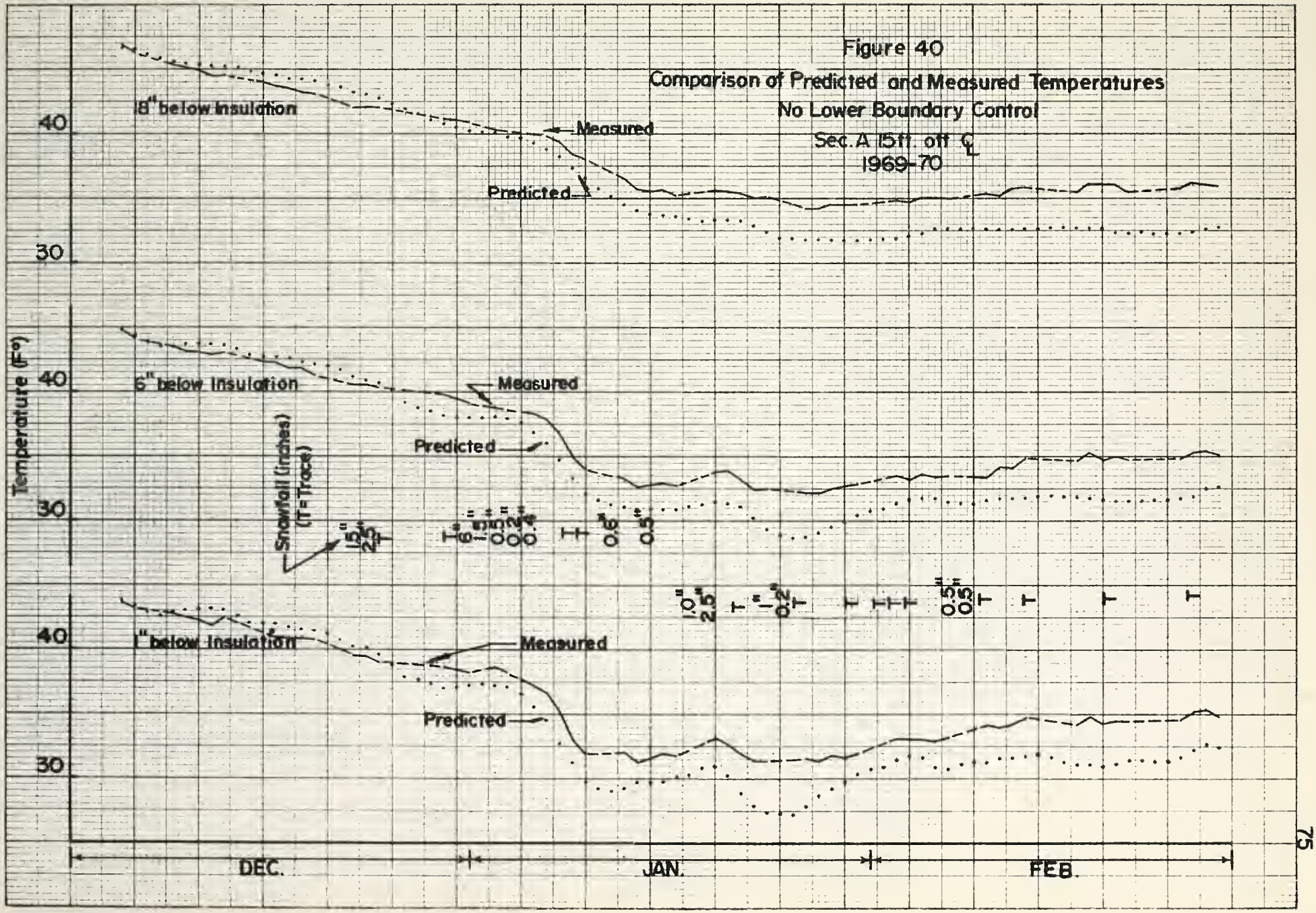


Figure 40
Comparison of Predicted and Measured Temperatures
No Lower Boundary Control
Sec. A 15ft. off $\mathcal{L}$
1969-70
18" below Insulation
Measured
Predicted
6" below Insulation
Measured
Predicted
1" below Insulation
Measured
Predicted
Temperature (F°)
40
30
Snowfall (inches)
(T=Trace)
1.5"
2.5"
T
0.6"
0.5"
1.0"
2.5"
0.2"
0.5"
DEC.
JAN.
FEB.

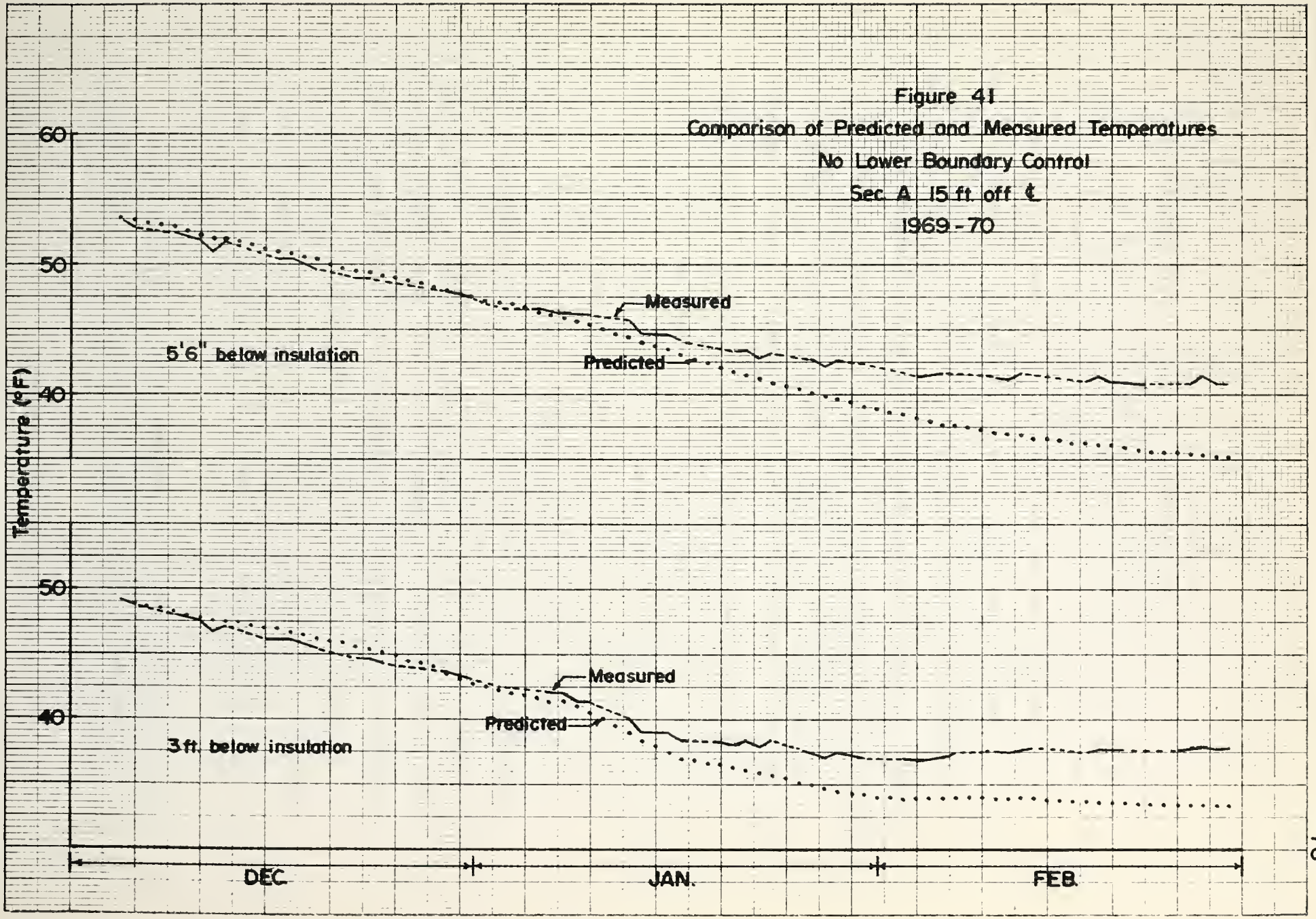


Figure 41
Comparison of Predicted and Measured Temperatures
No Lower Boundary Control
Sec A 15 ft. off ℄
1969-70
Temperature (°F)
60
50
40
5'6" below insulation
Measured
Predicted
50
40
3 ft. below insulation
Measured
Predicted
DEC.
JAN.
FEB.

of 1 to 2°F.

The initial error of as much as 2°F that appears on some of the curves may be due, at least partially, to the fact that temperature predictions were started on December 3, and the first comparisons were made on December 4. As a result, any errors introduced due to the straight line interpolation of the temperature distribution in the solution mesh on December 3 would tend to be present on December 4, since the elapsed time has not been great enough to allow the solution to converge to the correct temperature. It is thought that the initial error might have been significantly reduced if the temperature predictions had been started about 10 to 15 days prior to the date on which the initial comparisons were made. Note that the comparisons for 15 feet off the centerline (Figures 40 and 41) show no significant initial error. This is attributed to the fact that, below the subgrade surface, measured temperatures were available not only for the cells at that location, but, more importantly, for adjacent cells to the left and right of that location (see Figure 33). Thus that location is not likely to be significantly affected by temperature interpolation errors in other parts of the solution mesh. The initial error that does appear in many of the comparisons will decrease with time as the predicted temperature tends to converge to the correct temperature. Since the initial error (in this case) is relatively small, little, if any, of the initial error is likely to be present at the end of the freezing season.

In the upper part of the subgrade, cold periods appear to have a greater effect on the predicted temperatures than on the measured

temperatures. The comparisons for depths of 1, 6, and 18 inches below the insulation show that the difference between the predicted and measured temperatures increases during a moderate cold period in the latter part of December, and during two rather severe cold periods in January. A small portion of this error is due to incorrect lower boundary temperatures, but the major portion is attributed to a combination of snow cover and the fact that a surface transfer coefficient of 1.0 was used in the prediction program. A surface transfer coefficient (defined here as the ratio of the freezing index of the surface to the freezing index of the air) less than 1.0 should be used during cooling periods. Thus the upper boundary temperatures should be adjusted upwards during cooling periods, with the magnitude of the adjustment increasing as the air temperature decreases. The result would be higher predicted temperatures, since the rate at which heat is removed from the ground would be reduced. The fact that intermittent light snow cover between the shoulder points and snow cover on the slopes was not included in the prediction program would tend to cause the predicted temperatures to be lower than they should be, with the error increasing with increasing depth and/or duration of snow cover. That snow cover was sufficient, at least during portions of the 1969-70 freezing season, to significantly affect the ground temperatures is shown in Figure 40 where the daily snowfall is listed. Snowfall data were not collected at the test site. The snowfall data shown are for Lafayette. However, the data should be reasonably indicative of snow conditions at the test site.

Predicted temperatures were obtained for all three sections using a 2 inch thick bottom layer. Comparisons of predicted and measured

temperatures through January 23 for Sections B and C were very similar to those for Section A, with the comparisons for Section B being slightly worse than for A, and those for Section C slightly better than for A. However, the predictions were made using the design cross sections, which were later found to differ somewhat from the as-built cross sections, especially in the slope areas. It was then decided that little useful information would be obtained by rerunning all three sections, since the earlier comparisons for the three sections were very similar through January 23, and that more information could be obtained by rerunning only one section (Section A) and concentrating on the problem of the lower boundary temperatures. Thus most of the results shown in this part of the report are for Section A.

The comparisons shown in Figures 36 through 41 show increasing error after January 23, and by the end of February the error is quite large. Much of the error, at least for the deeper locations is due to increasing error in the predicted lower boundary temperature. Figure 42 shows comparisons of predicted and measured temperatures for the deepest thermistors on the centerline for all three sections. The predicted temperatures shown for Sections B and C are those that were obtained using the design cross sections, but for the location being considered here the error resulting from the use of a moderately incorrect section will be very small. The agreement between measured and predicted temperatures is reasonably good in Section B, but bad in Sections A and C. This is attributed to the fact that the actual temperature gradients at the lower boundaries of the sections increase as one goes from Section B to A to C, and thus the error introduced

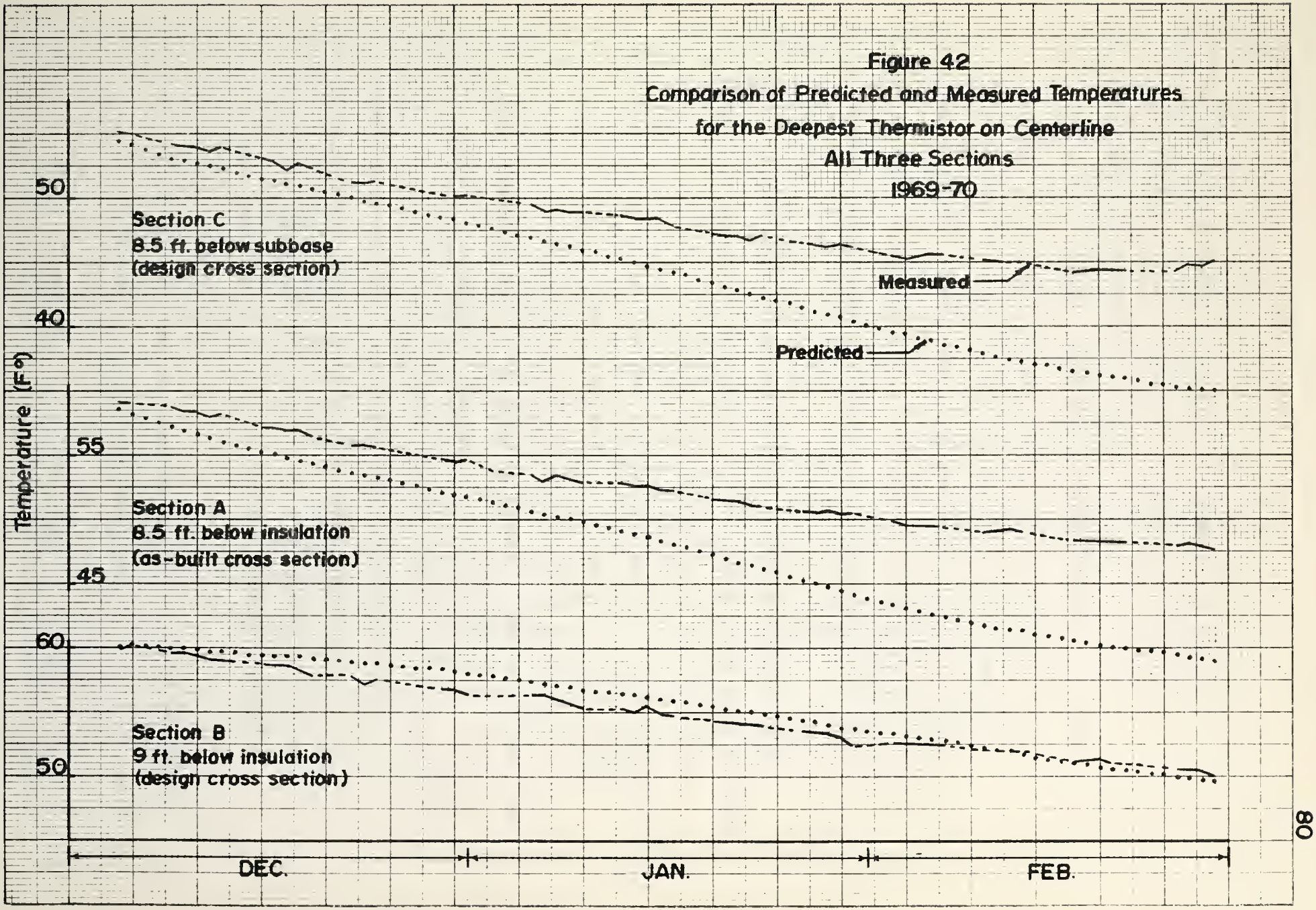


Figure 42
Comparison of Predicted and Measured Temperatures
for the Deepest Thermistor on Centerline
All Three Sections
1969-70
Temperature (F°)
50
40
55
45
60
50
Section C
8.5 ft. below subbase
(design cross section)
Measured
Predicted
Section A
8.5 ft. below insulation
(as-built cross section)
Section B
9 ft. below insulation
(design cross section)
DEC.
JAN.
FEB.

at the lower boundary as a result of transferring the lower layer temperature to the lower boundary for the next prediction will tend to increase in the same order.

Since the predicted and measured temperatures for the lower boundary in Section B agree reasonably well throughout the period from December 4 to February 28, significantly better agreement between predicted and measured temperatures at higher elevations would be expected in this section. The comparisons that were made using predicted temperatures for the design cross section show this to be the case.

To find out what kind of agreement would be obtained between predicted and measured temperatures in Section A if the lower boundary temperatures could be accurately predicted, the 2 inch thick lower layer was eliminated from the solution mesh and the lower boundary was placed at the elevation of the deepest thermistors. The solution was then rerun using actual measured temperatures as the lower boundary temperatures (Lower Boundary Control). The results are shown in Figures 43 through 48. Comparison of these Figures to Figures 36 through 41 shows that significant improvement is obtained for the period from January 23 to February 28, with some improvement prior to January 23. Figure 49 shows temperature vs. depth plots for the centerline of Section A on February 10. The improvement in the predicted temperatures as a result of Lower Boundary Control is illustrated in the figure.

In the design of an insulated highway the time span of interest is the frost penetration period, and the elevation of primary interest

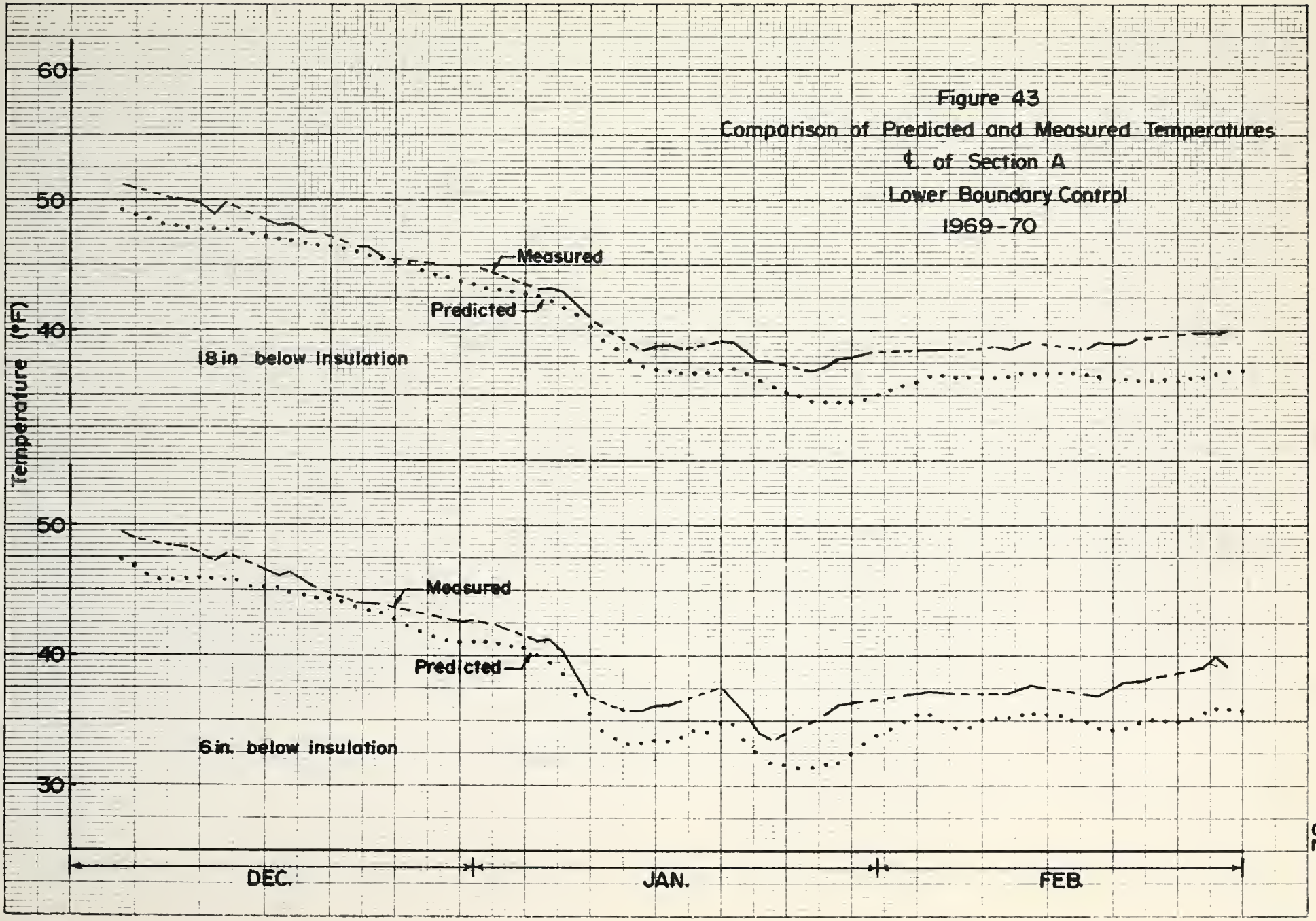


Figure 43
Comparison of Predicted and Measured Temperatures
℄ of Section A
Lower Boundary Control
1969-70
Temperature (°F)
60
50
40
Measured
Predicted
18 in below insulation
50
40
30
Measured
Predicted
6 in. below insulation
DEC.
JAN.
FEB

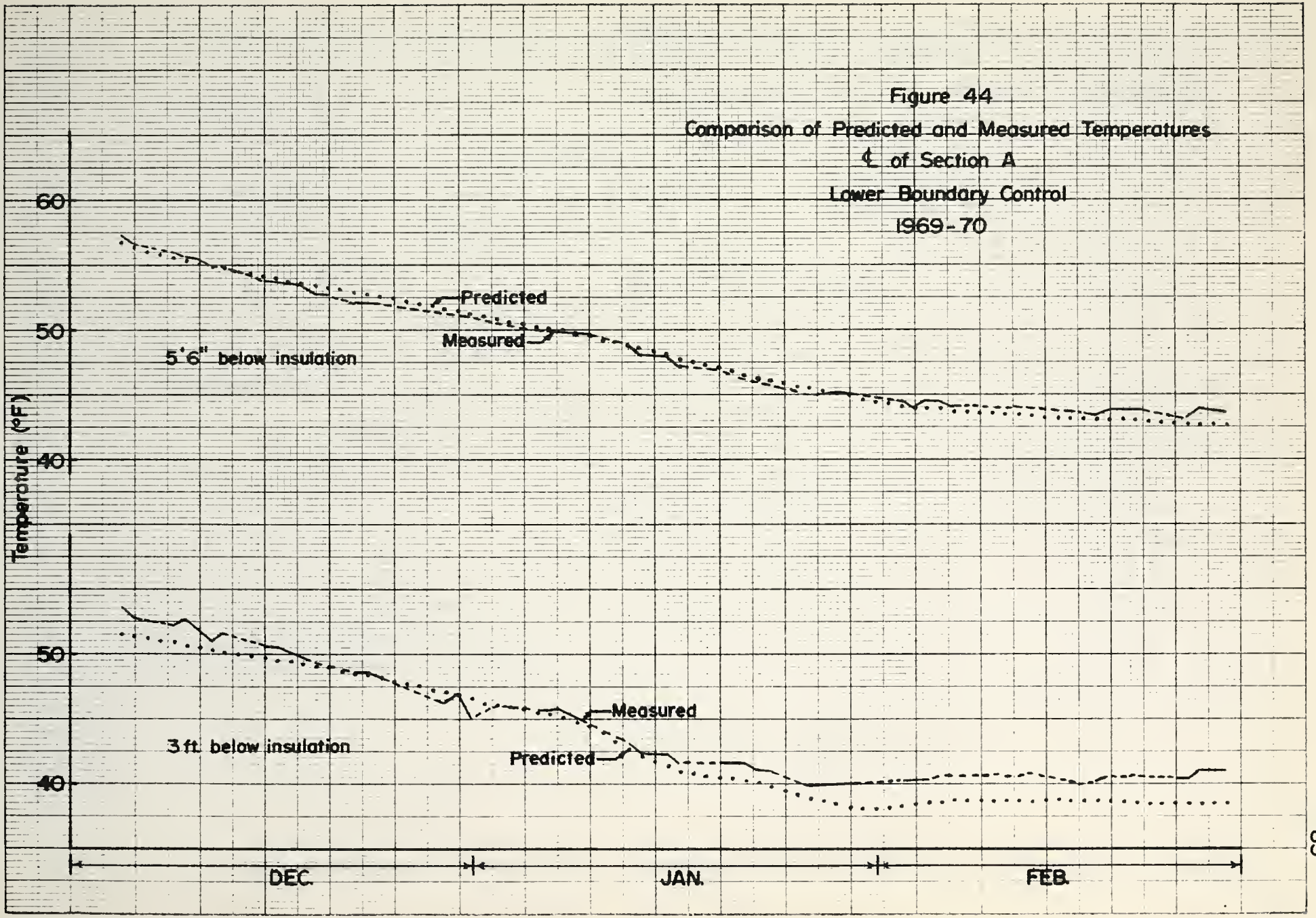


Figure 44
Comparison of Predicted and Measured Temperatures
℄ of Section A
Lower Boundary Control
1969-70
Temperature (°F)
60
50
40
Predicted
Measured
5'6" below insulation
50
40
Measured
Predicted
3 ft. below insulation
DEC.
JAN.
FEB.

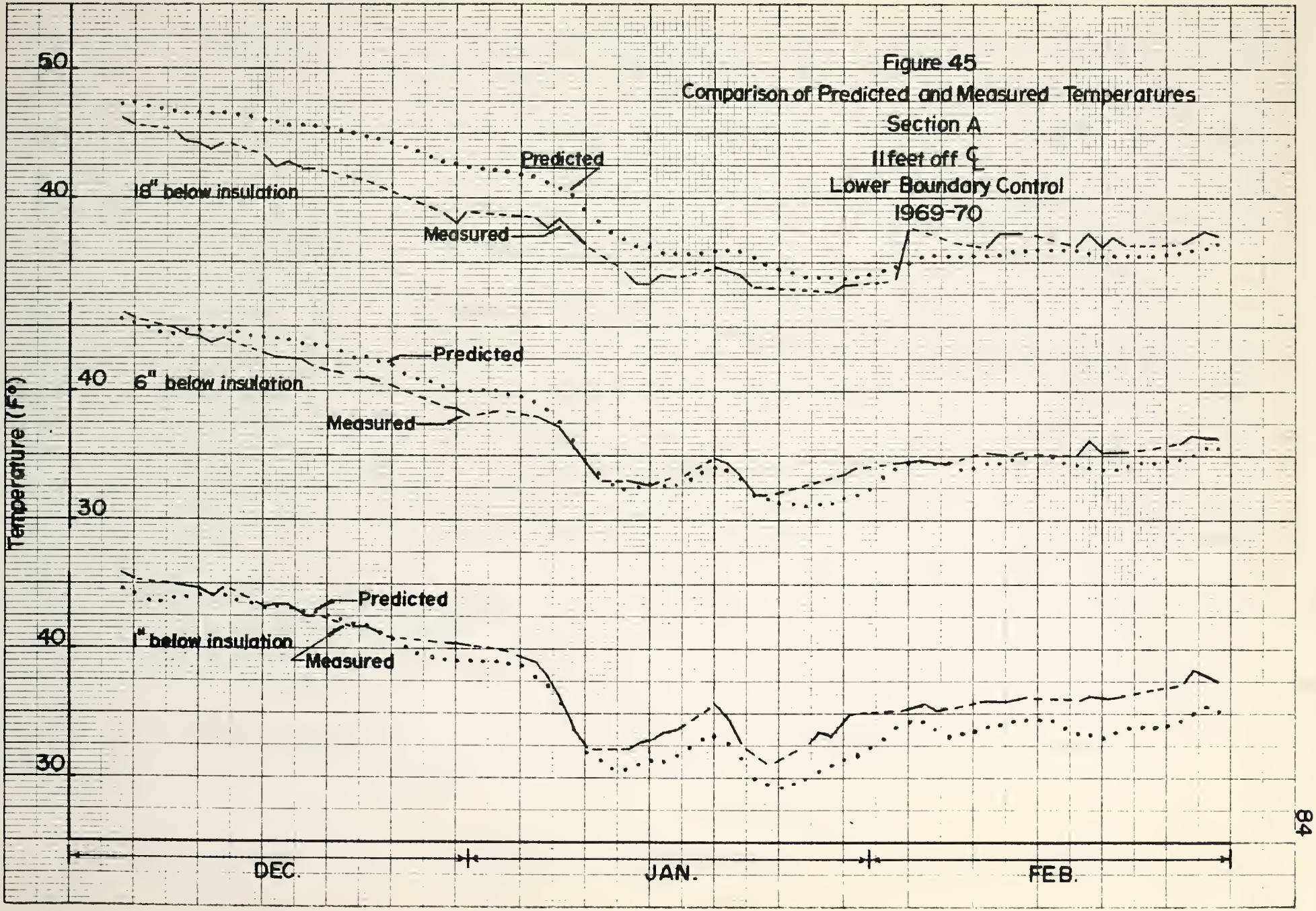


Figure 45
Comparison of Predicted and Measured Temperatures
Section A
11 feet off ℄
Lower Boundary Control
1969-70
Temperature (F°)
50
40
30
18" below insulation
Predicted
Measured
6" below insulation
Predicted
Measured
1" below insulation
Predicted
Measured
DEC.
JAN.
FEB.

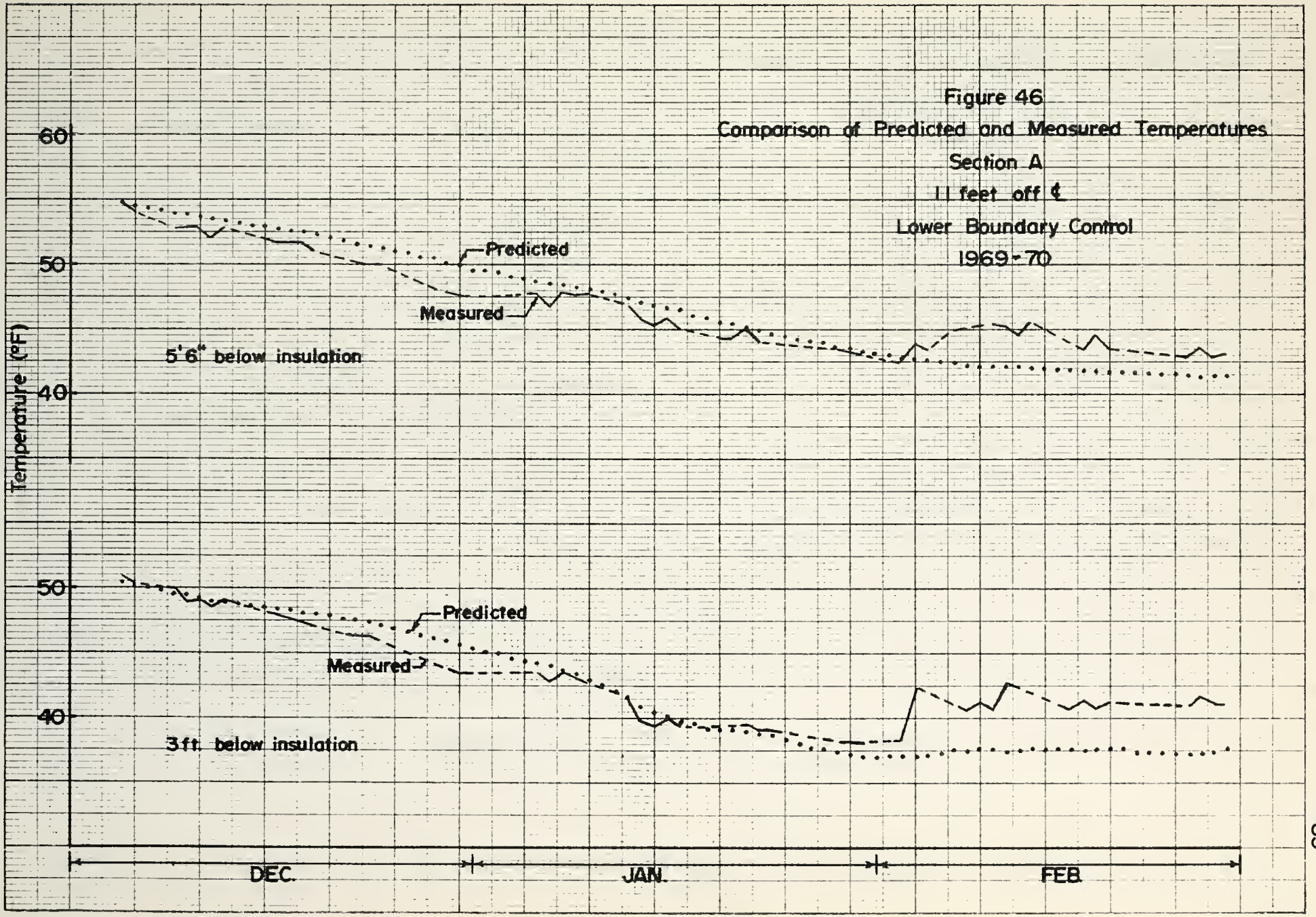


Figure 46
Comparison of Predicted and Measured Temperatures
Section A
11 feet off ℄
Lower Boundary Control
1969-70
Temperature (°F)
60
50
40
Predicted
Measured
5'6" below insulation
50
40
Predicted
Measured
3ft. below insulation
DEC.
JAN.
FEB

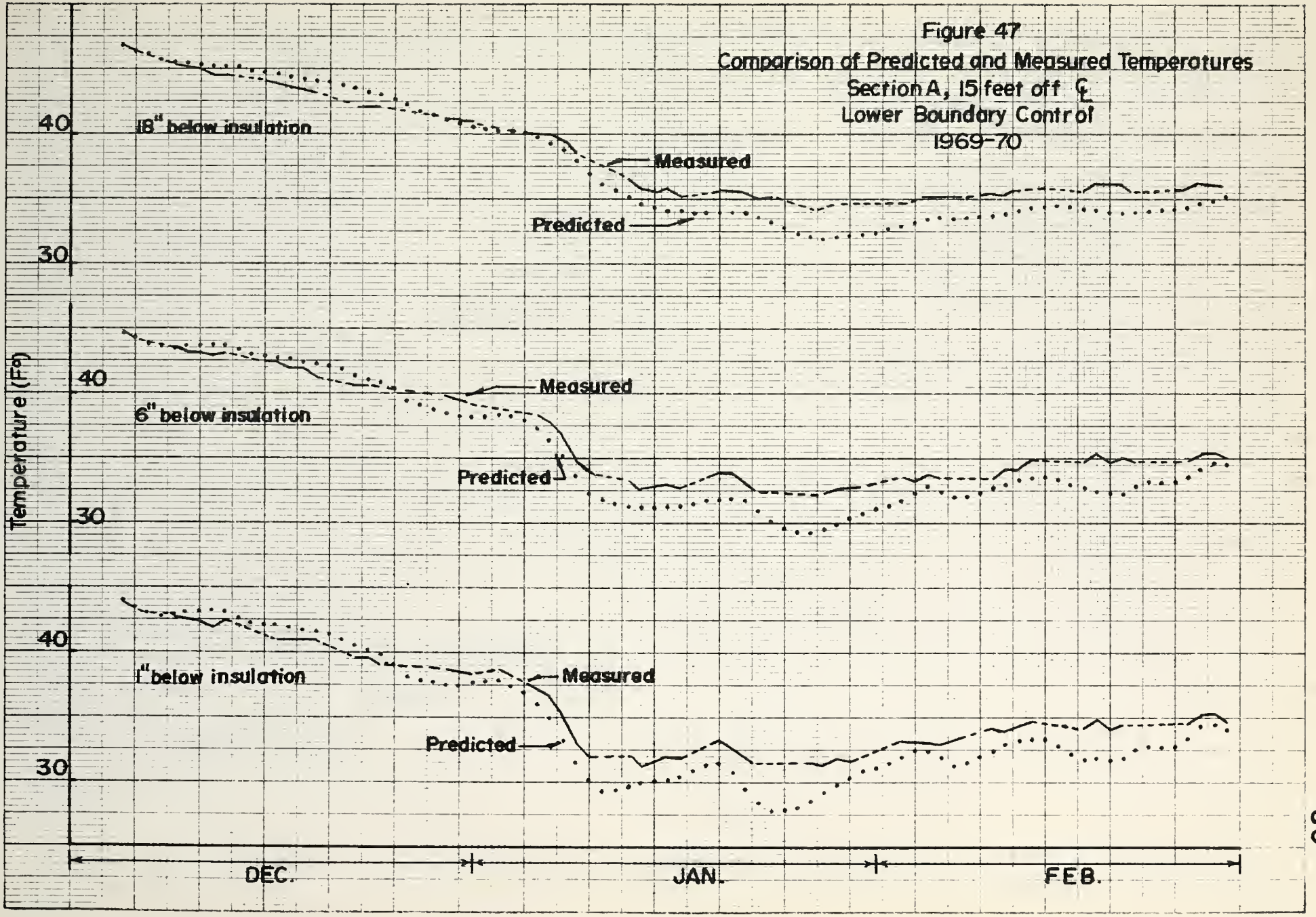


Figure 47
Comparison of Predicted and Measured Temperatures
Section A, 15 feet off ℄
Lower Boundary Control
1969-70
Temperature (Fº)
40
30
18" below insulation
Measured
Predicted
6" below insulation
1" below insulation
DEC.
JAN.
FEB.

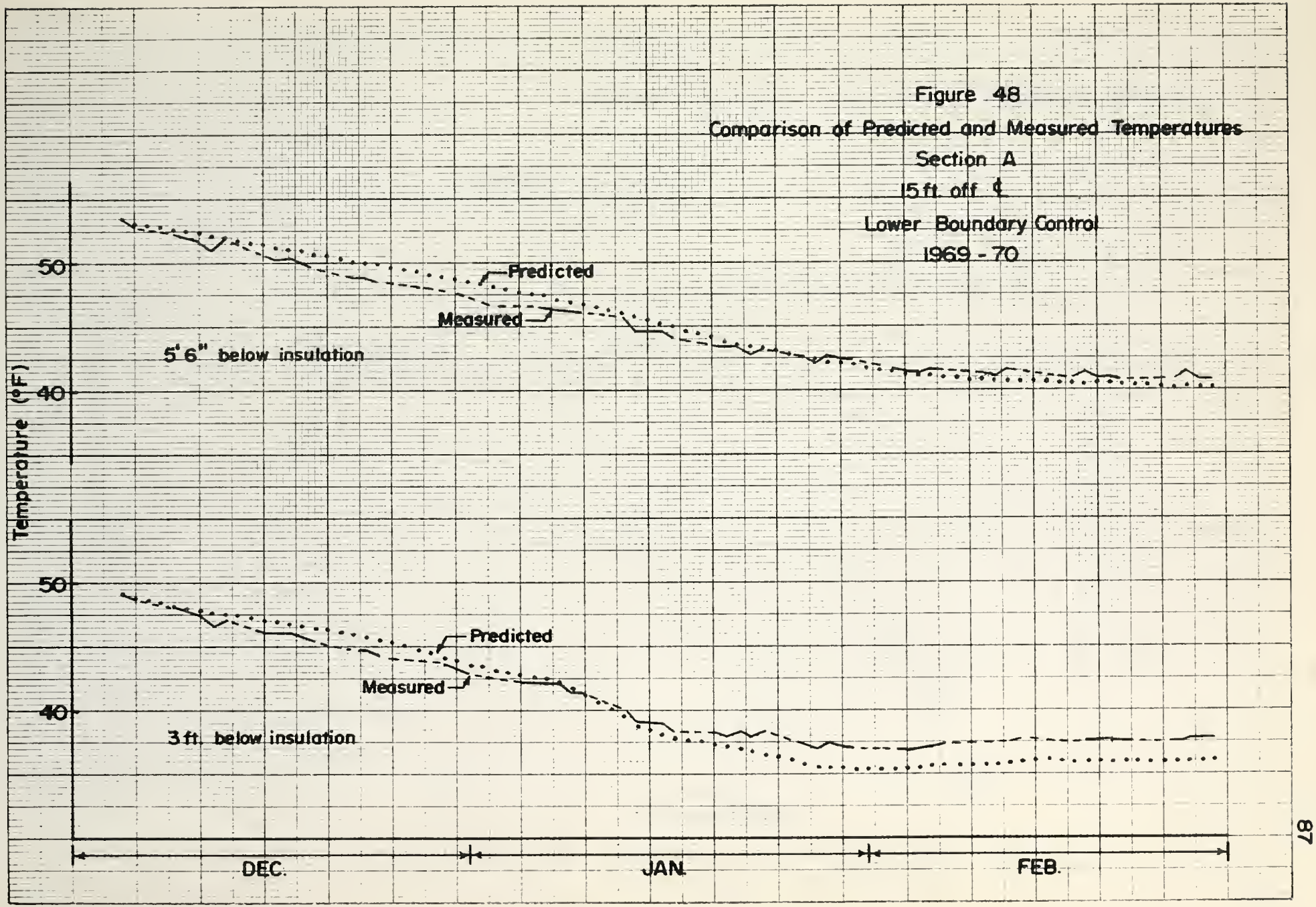


Figure 48
Comparison of Predicted and Measured Temperatures
Section A
15 ft. off ℄
Lower Boundary Control
1969 - 70
Temperature (°F)
50
40
Predicted
Measured
5' 6" below insulation
50
40
Predicted
Measured
3 ft. below insulation
DEC.
JAN.
FEB.

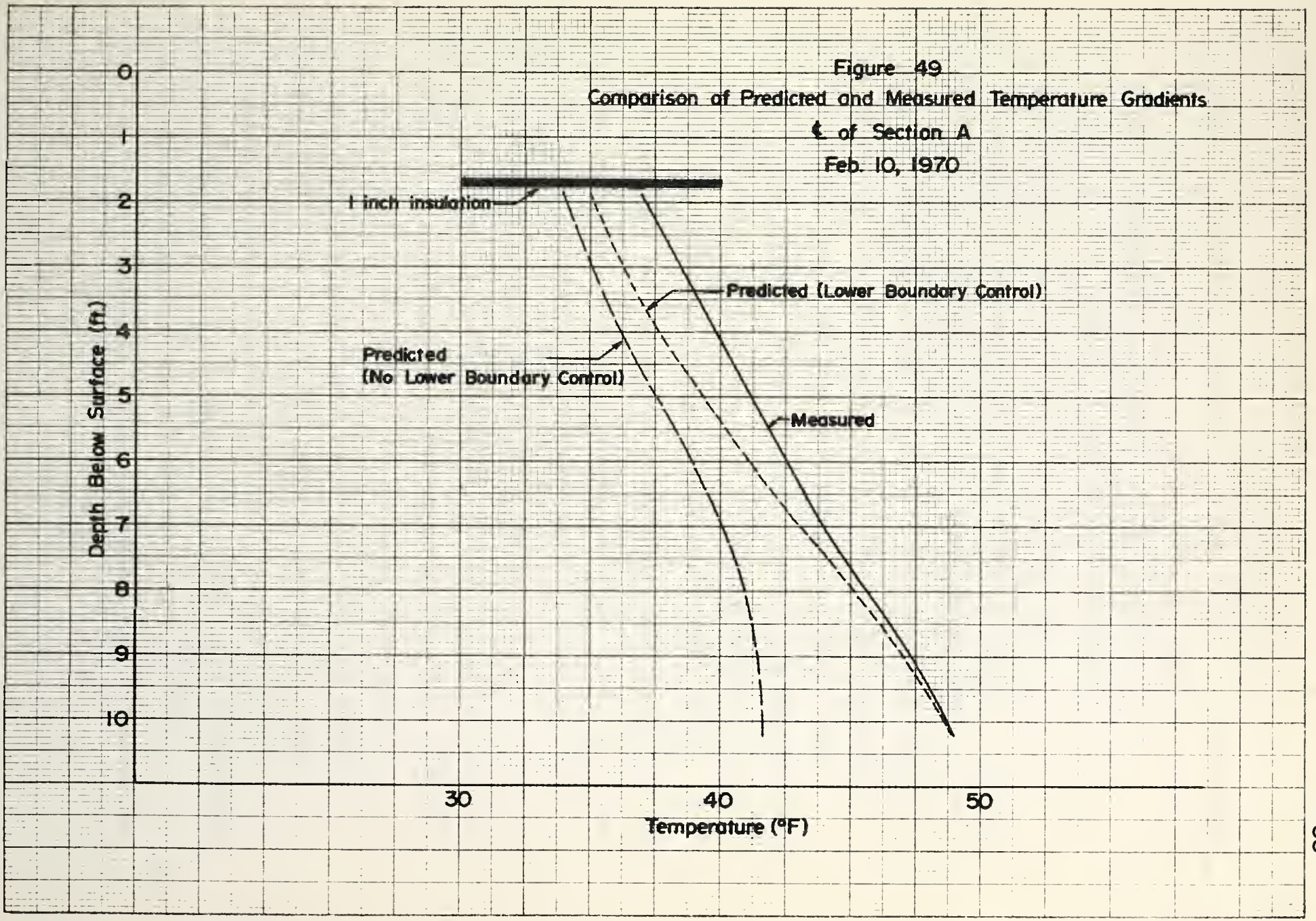


Figure 49
Comparison of Predicted and Measured Temperature Gradients
℄ of Section A
Feb. 10, 1970
1 inch insulation
Predicted (Lower Boundary Control)
Predicted
(No Lower Boundary Control)
Measured
Depth Below Surface (ft.)
0
1
2
3
4
5
6
7
8
9
10
30
40
50
Temperature (°F)

is that just under the insulation. For the condition of Lower Boundary Control, the error prior to January 23 (during the frost penetration period) is reduced by only $0.5^{o}F$ or less in the region near the insulation. As a result, one might conclude that improving the lower boundary temperature predictions would be of little value. However, the magnitude of the error at a given elevation depends on the position of the lower boundary as well as on the error in the predicted lower boundary temperature. Also, the error in predicted lower boundary temperatures will depend on the initial lower boundary temperatures, if estimated, and on the severity of the freezing season. These factors are likely to combine in such a way that the error in predicted temperatures in the upper portion of the subgrade during the frost penetration period will be significantly greater than the $0.5^{o}F$ obtained here. Thus improvement in the prediction of the lower boundary temperatures would be highly desirable, especially if this can be done will little or no increase in computer cost. As stated previously, Mr. Horton is currently working on this problem.

Snow cover was discussed earlier, but its effect is particularly apparent in the comparisons of measured and predicted temperatures for locations at the shoulder point and beyond, where snow cover is allowed to accumulate. Figures 50, 51 and 52 show such comparisons for Section A for the case of no lower boundary control. Daily snowfall is shown on Figure 50. The data show that considerable snow cover was present during the major cold periods. Since the insulating affect of the snow cover was not considered in the temperature predictions, considerable discrepancies between predicted and measured

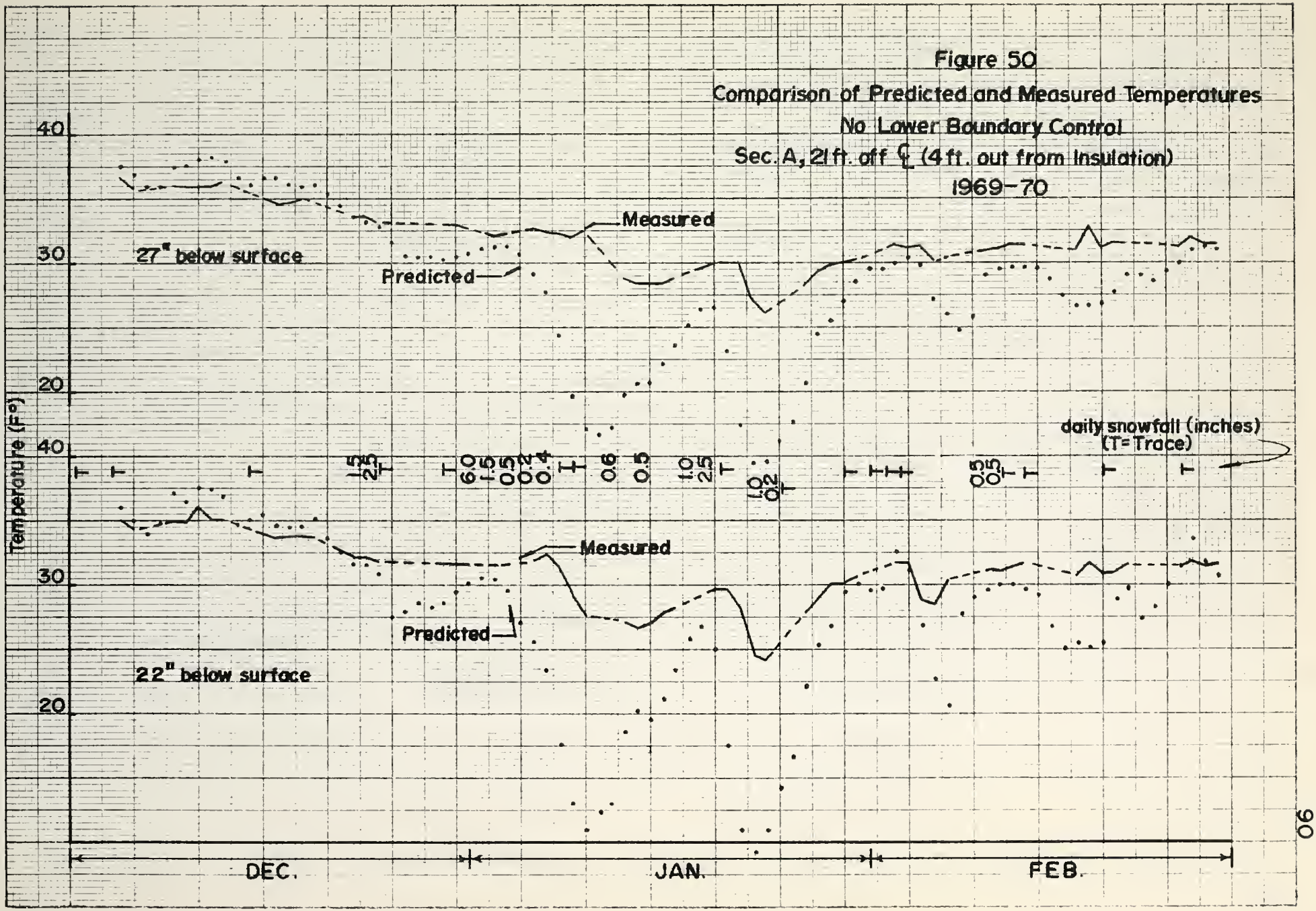


Figure 50
Comparison of Predicted and Measured Temperatures
No Lower Boundary Control
Sec. A, 21 ft. off ℄ (4 ft. out from Insulation)
1969-70
Temperature (F°)
40
30
20
27" below surface
Measured
Predicted
22" below surface
daily snowfall (inches)
(T= Trace)
DEC.
JAN.
FEB.

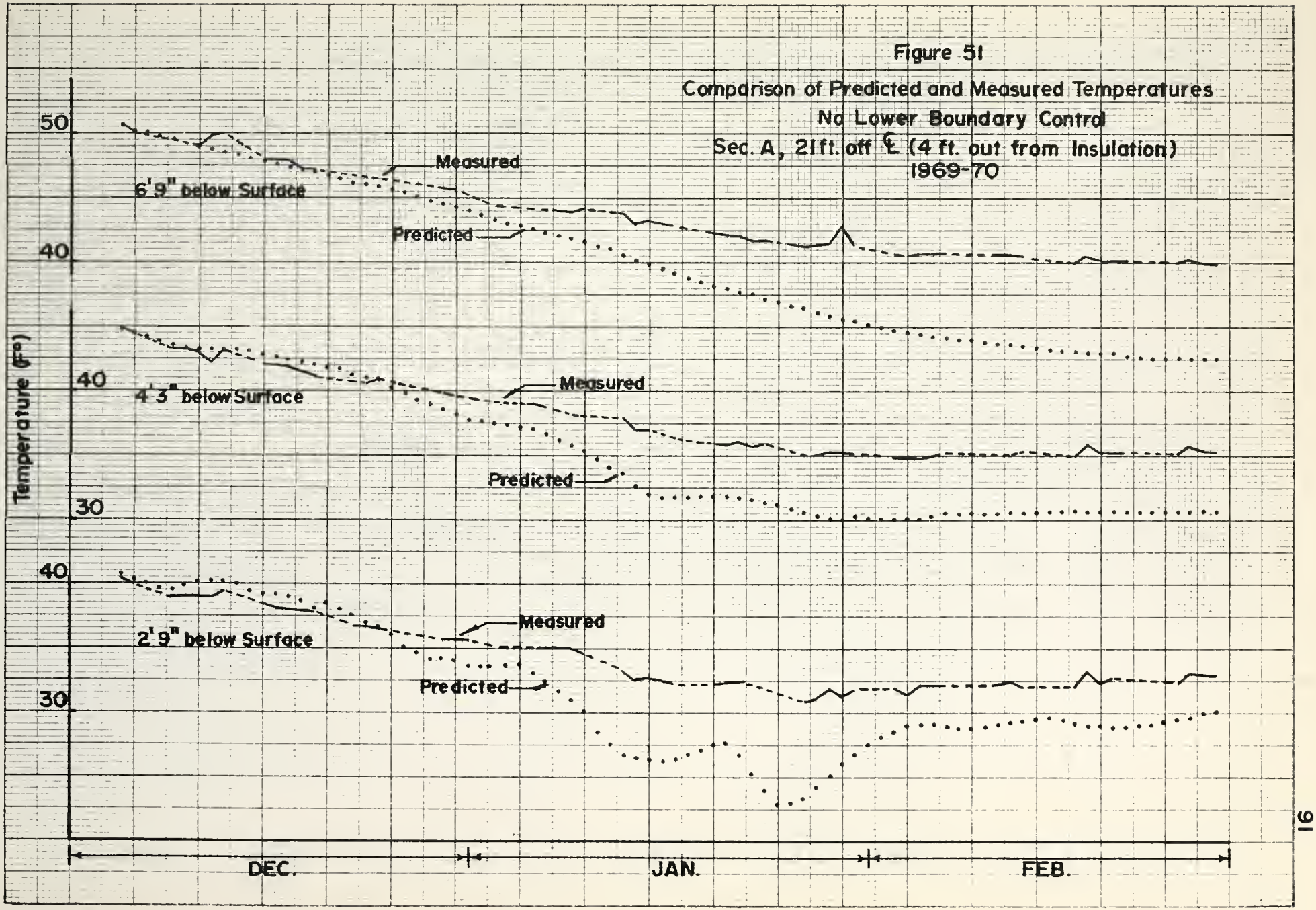


Figure 51
Comparison of Predicted and Measured Temperatures
No Lower Boundary Control
Sec. A, 21ft. off ℄ (4 ft. out from Insulation)
1969-70
Temperature (F°)
50
40
40
30
40
30
Measured
6'9" below Surface
Predicted
Measured
4'3" below Surface
Predicted
Measured
2'9" below Surface
Predicted
DEC.
JAN.
FEB.

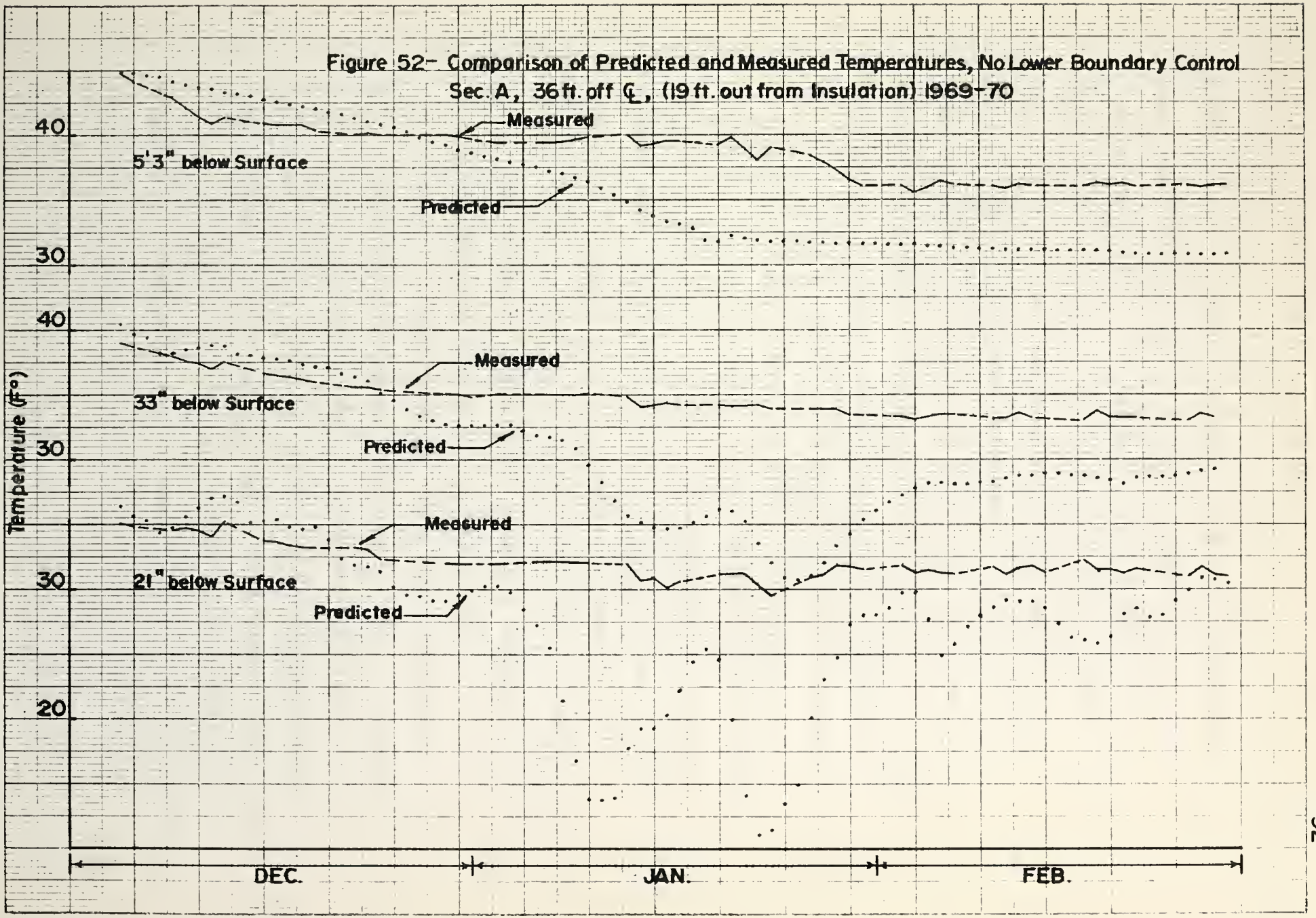


Figure 52- Comparison of Predicted and Measured Temperatures, No Lower Boundary Control
Sec. A, 36 ft. off ℄, (19 ft. out from Insulation) 1969-70
Measured
5'3" below Surface
Predicted
Measured
33" below Surface
Predicted
Measured
21" below Surface
Predicted
Temperature (F°)
40
30
40
30
30
20
DEC.
JAN.
FEB.

temperatures would be expected during the cold periods, with the discrepancies decreasing with increasing depth of ground cover over the thermistors. Thus the discrepancies that appear in the figures during cold periods are not particularly surprising. Note that the snow cover attenuates both the cooling and the warming effect of the air temperature, as indicated by the fact that the measured temperature curve is much smoother than the curve for the predicted temperatures, especially for the thermistors at the higher elevations. In addition, comparing the measured temperature curves for 22 inches below the surface in Figure 50 and for 21 inches below the surface in Figure 52 shows the effect of snow removal on the shoulders. The curve in Figure 50 is for 21 feet off the centerline (near the shoulder point), while the one in Figure 52 is for 36 feet off the centerline. Note that the curve in Figure 52 is much smoother than the one in Figure 50. This is attributed primarily to the fact that at 36 feet off the centerline snow cover is present on both sides of the thermistor column at that location, whereas at 21 feet off the centerline the snow cover is generally present only on the slope side of the thermistor column. As a result, the ground temperatures 21 feet out respond more readily to the air temperatures than do the ground temperatures at 36 feet out. While some of the difference is due to differences in the soils at the two locations, the major portion of the difference is due to the difference in snow cover.

As mentioned earlier, the error between predicted and measured temperatures in the slope area will tend to cause error in the predicted temperatures throughout the section, with the error decreasing with

increasing distance from the slope.

For the deeper thermistors, the effect of the cumulative error in the prediction of the lower boundary temperatures is again apparent. The results of rerunning the curves with Lower Boundary Control are shown in Figures 53, 54, and 55. These curves show significant improvement occurs, for the deeper thermistors, in the late January through February period with Lower Boundary Control. Only minor improvement is noted at the higher elevations.

Examination of the curves in Figures 50 through 52 indicates that a rough approximation of the correct temperatures at the higher elevations could be obtained by drawing smooth curves through the high points on the temperature prediction curves. However, the reliability of this approach for increases in depth and duration of snow cover, and for increases in the severity of the freezing season is certainly open to question.

If the capability of handling snow cover could be included in the computer program, significant reduction in the error between measured and predicted temperatures could be obtained, especially in the slope area. However, due to both the restrictions on drawing the finite difference solution mesh and the fact that the snow cover depth, duration, and properties change throughout the freezing season, an inclusion of snow cover in the computer program will not be easy and any method used is likely to be approximate at best. Nevertheless, the results obtained in this study indicate that some reasonable method must be found to include the slope snow cover in the computer program, especially for areas where snow cover depth and/or duration is

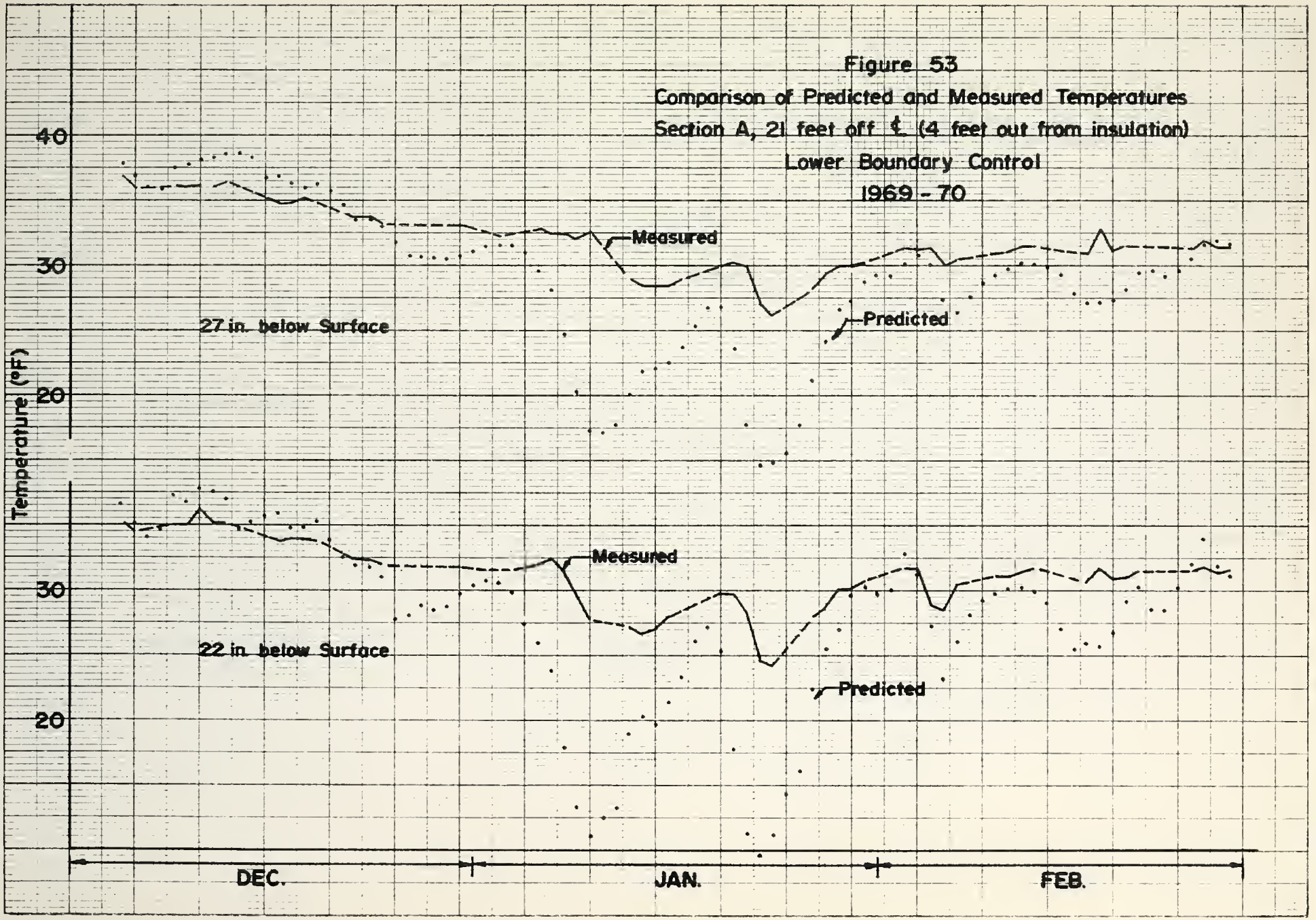


Figure 53
Comparison of Predicted and Measured Temperatures
Section A, 21 feet off ℄ (4 feet out from insulation)
Lower Boundary Control
1969 - 70
Temperature (°F)
40
30
20
27 in. below Surface
Measured
Predicted
30
20
22 in. below Surface
Measured
Predicted
DEC.
JAN.
FEB.

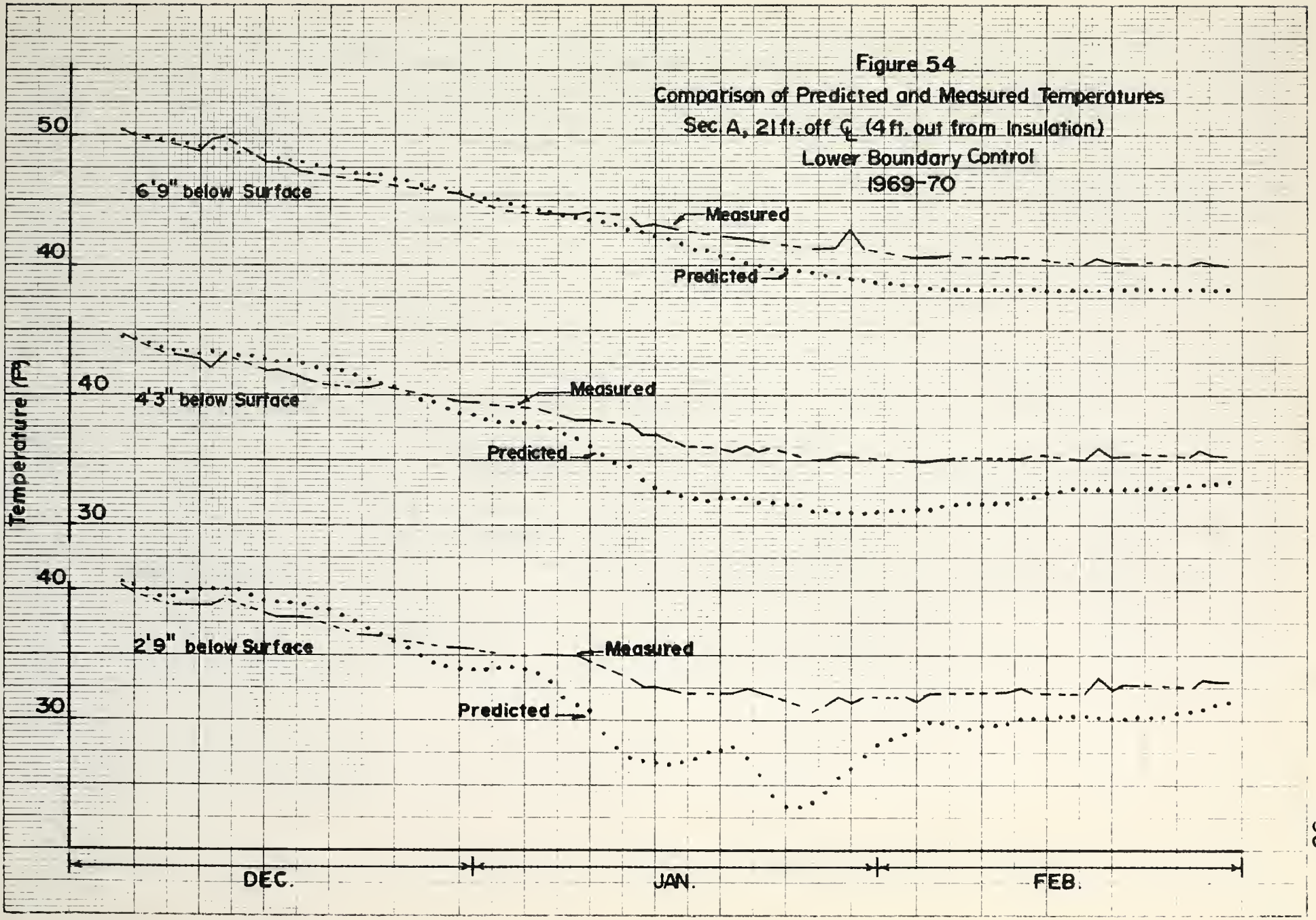


Figure 54
Comparison of Predicted and Measured Temperatures
Sec A, 21ft. off ℄ (4ft. out from Insulation)
Lower Boundary Control
1969-70
Temperature (°F)
50
40
6'9" below Surface
Measured
Predicted
40
30
4'3" below Surface
Measured
Predicted
40
30
2'9" below Surface
Measured
Predicted
DEC.
JAN.
FEB.

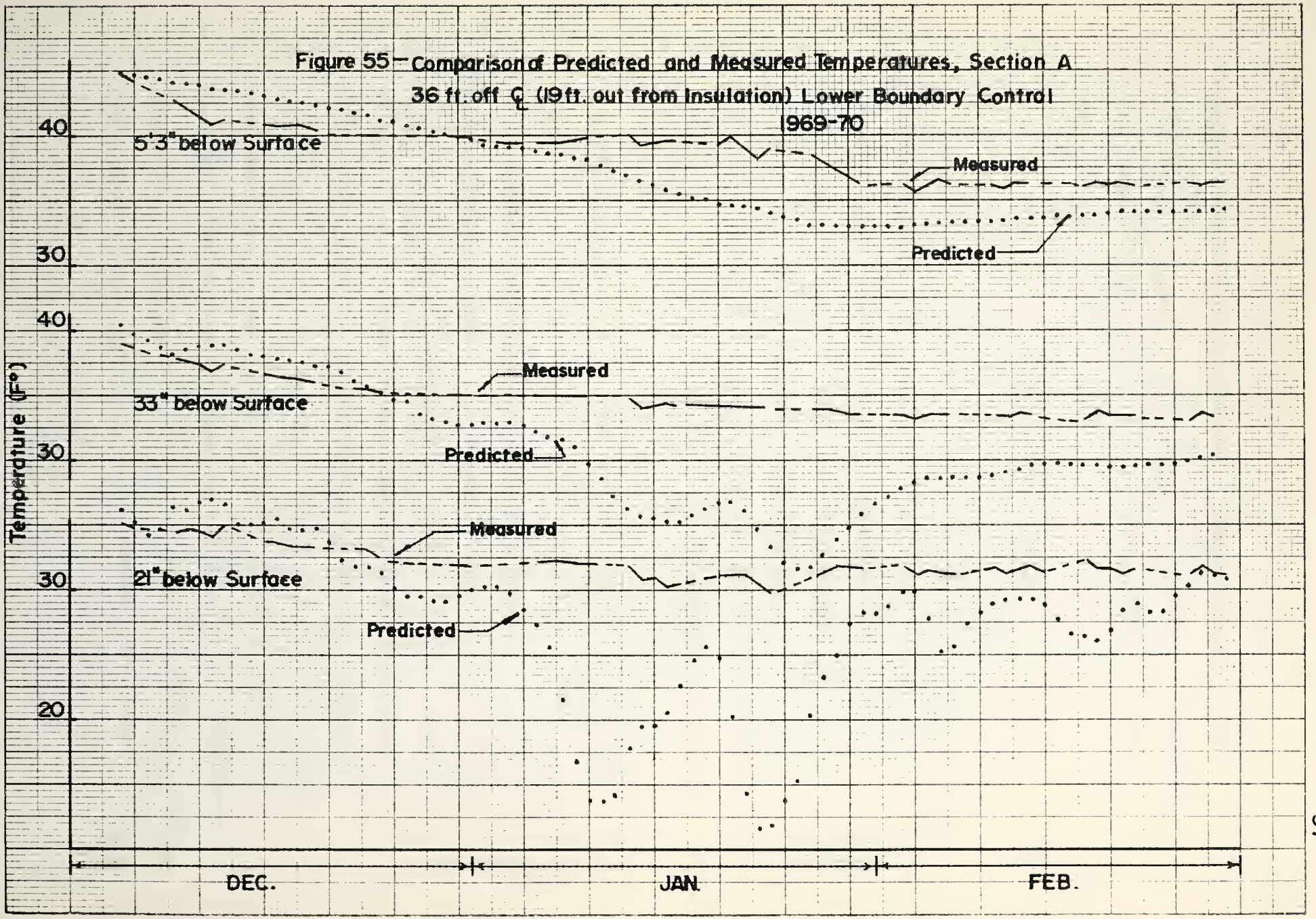


Figure 55 – Comparison of Predicted and Measured Temperatures, Section A
36 ft. off ℄ (19 ft. out from Insulation) Lower Boundary Control
1969-70
5'3" below Surface
Measured
Predicted
33" below Surface
Measured
Predicted
21" below Surface
Measured
Predicted
Temperature (F°)
40
30
40
30
30
20
DEC.
JAN.
FEB.

greater and where the severity of the freezing season is greater. As mentioned previously, Mr. Horton is currently planning to investigate possible methods of including the slope snow cover in the computer program.

SUMMARY AND CONCLUSIONS

The analysis of the data obtained for the 1969-70 freezing season has been completed. The results of the analysis show that the installation of a thermal barrier at the subgrade surface will significantly change the thermal regime in a highway section. Significantly higher temperatures are maintained in the subgrade beneath the insulation, and this results in either elimination of, or a significant reduction in the depth of frost penetration into the subgrade.

How effective a thermal barrier will be for a given freezing season depends primarily on the width, thickness and thermal conductivity of the thermal barrier, and on the depth at which the thermal barrier is placed. For the test installation there was no significant frost penetration into the subgrade at the centerline of the insulated sections, whereas the frost penetrated about 30 inches into the subgrade of the uninsulated section. In addition, the 1.5-inch thick, 46-feet wide insulation in Section B was much more effective than the 1-inch thick, 36-feet wide insulation in Section A, even though the insulation in Section A was placed 6 inches lower in the highway section. Although there was no significant frost penetration into the subgrade of either insulated section during the

relatively "mild" 1969-70 freezing season, the data indicate that for the more "severe" Indiana winters some frost penetration into the subgrade of both insulated sections can be expected, with Section A being more susceptible than Section B.

Some pavement cracking has developed in the insulated sections, but at the present time the cracking cannot be attributed to the presence of the insulation, because the crack patterns are not inconsistant with crack patterns that have developed outside the test area.

The relatively crude analysis of the surface icing problem indicates that differential icing between the surfaces of insulated and uninsulated sections can be expected, and that the general trend in temperatures at the time an icing situation arises may determine which section is the critical one.

The results of the temperature prediction phase of the study are definitely encouraging. The agreement obtained between predicted and measured temperatures for the frost penetration period is considered to be sufficient to justify using the 2-D program to evaluate alternate thermal designs. However, the study has indentified two parts of the prediction program that should be improved. These are the prediction of the lower boundary temperatures, and the inclusion of the slope snow cover. These two problems are currently being studied by Mr. Horton.

Data are being taken at the site for the current (1971-72) freezing season, with ground temperatures generally being taken two days per week instead of daily. Attempts are being made to observe differential surface icing on the sections during the current season.

RECOMMENDATIONS

General

The problem of differential surface icing on insulated sections needs further study. The potential severity of the problem needs to be determined so that, if necessary, future installations can be designed to minimize the problem.

Assuming that Mr. Horton's efforts to include snow cover in the prediction program are successful, the program should then be checked against actual field data for a location where slope snow cover is sufficient to prevent frost penetration in the slope area.

Consideration should be given to the development of a 2-D temperature prediction program based on the method of finite elements. Such a program would offer greater flexibility in fitting section and material boundaries, and, in addition, may offer a significant reduction in computer cost.

Test Site

With regard to continued data collection at the site, it is recommended that observations of air and ground temperatures be obtained for future freezing seasons in an attempt to get data for a freezing season that is much more "severe" than the two seasons of record. For future freezing seasons it is recommended that ground temperature observations initially be taken only once per week, coincident with the changing of the thermograph chart. If, for a given freezing season, there is no significant accumulation of freezing degree days by the first week of January, data collection for that

season can be stopped, since it is unlikely that the season will be "severe". Thus, 4 to 6 sets of observations would be required at the beginning of each freezing season to determine the potential severity of the season. If, by the first week of January, a "severe" season appears likely, observations would be continued through the season, in which case it would be desirable to increase the frequency of ground temperature observations to a minimum of twice per week for the remainder of the season. It is, of course, necessary that enough of the thermistors continue to operate properly to permit analysis of the data.

Periodic inspection of pavement cracking over both insulated and uninsulated sections of the highway is recommended. If the rate of deterioration of the pavement is significantly faster over the insulated sections (especially Section B), this would tend to indicate that the insulation was placed too high in the sections, and, as a result, the structural performance of the sections was affected.

A record of differential surface icing on the test sections should be obtained for several freezing seasons. Unfortunately, obtaining data on the frequency and severity of actual icing conditions is difficult, since icing will generally occur when personnel directly connected with the project are not present to observe it.

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APPENDIX

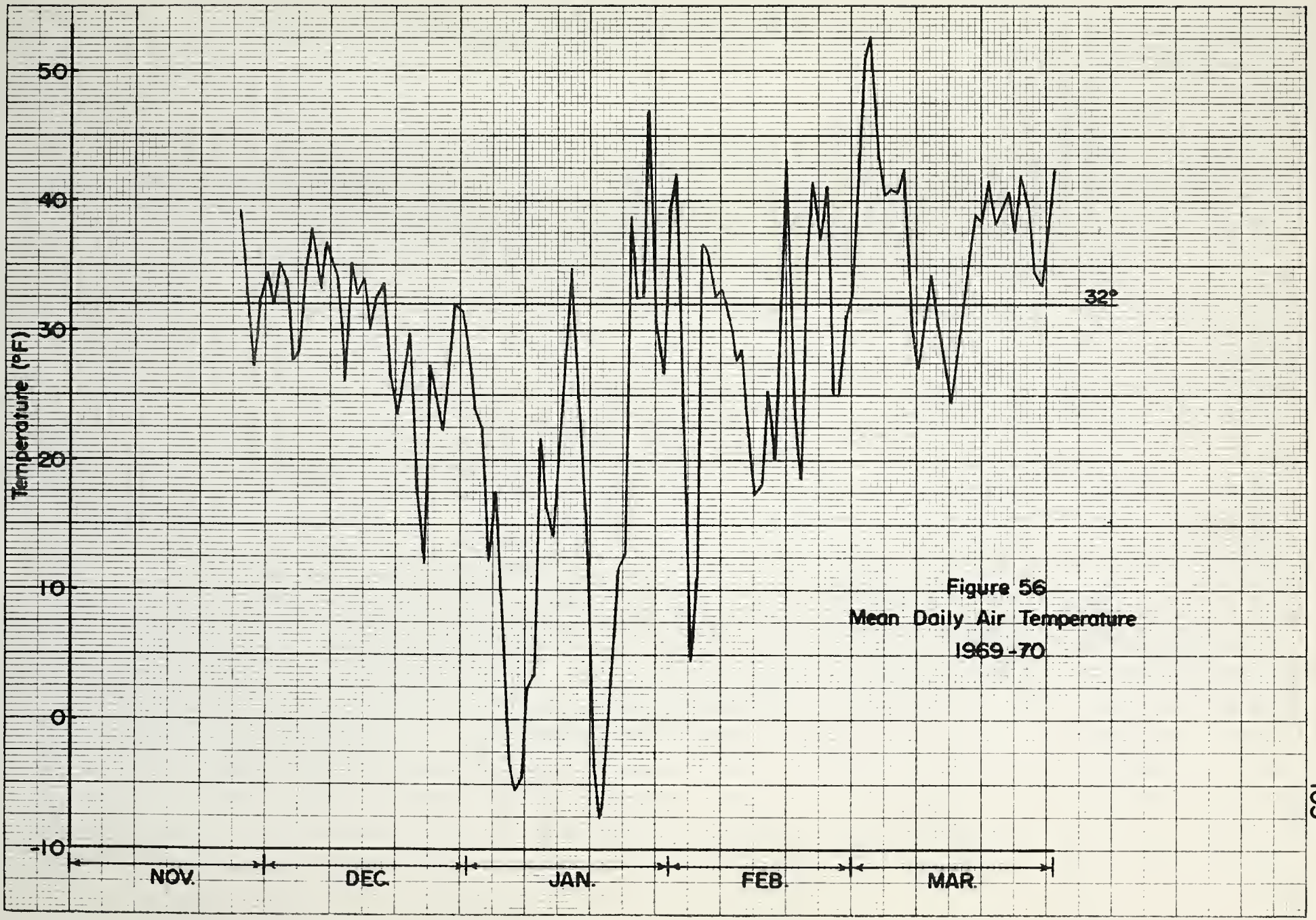

Figure 56
Mean Daily Air Temperature
1969-70